HAMILTON HARBOUR STUDY

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Ministry of the Environment

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HAMILTON HARBOUR STUDY

Table of Contents

HAMILTON HARBOUR

Description of Harbour

Hamilton Harbour is an enclosed body of fresh water at the western end of Lake Ontario approximately 8 km (5 miles) in the east-west direction and 4.8 km (3 miles) in the north-south direction. It is connected by a ships' canal 732 m (2400 feet) long by 107 m (350 feet) wide and 9 m (30 feet) deep to Lake Ontario. The harbour contains approximately 2.8×10^8 m^3 (9.9×10^9 $feet^3$) of water with a mean depth of 13 m (43 feet). Hamilton Harbour receives drainage from a watershed of 500 km^2 (190 mi^2) through several small creeks which drain into the harbour with a total annual flow of 1.27×10^8 m^3 (2.8×10^4 MIG) consequently, the natural throughput is approximately 45 percent per year.

The industries located on the highly developed south shore use 27 m^3/sec (510 MIGD) water as an industrial supply, returning a similar amount of effluent to the harbour. They also depend upon the harbour for shipping of raw materials and finished products.

Municipal utilities also use the harbour as a receiving water for 3.2 m^3/sec (61 MIGD) of treated wastes and for untreated storm sewer overflows estimated at 0.1 m^3/sec (1.9 MIGD) during overflow periods. Together with the natural flow, this results in a total annual flow of 2.3×10^8 m^3, or a throughput of approximately 80 percent per year. Presently, the harbour is also used for recreational boating.

As the harbour shoreline is extensively developed, the industries, Hamilton Harbour Commissioners and private developers have adopted landfilling as a technique for acquiring new land for expansion for many years. Concern has been voiced that the landfilling program will deplete an irreplacable water resource and the landfilling has also become the object of public concern lest the water quality of the harbour be degraded. Both industry and the municipalities recognize the importance of the harbour water quality and have installed treatment facilities. While it is unlikely that the water quality in the harbour regions directly adjacent to the industrial shoreline can be brought to a level which meets the criteria for fish, wildlife and recreation, these criteria could be achieved in the remaining portions of the harbour.

Purpose of the Study

In 1972, the Ontario Ministry of the Environment undertook a water quality study of the harbour. The objectives of the study were: to determine existing water quality and its trends over recent years; to identify problems and recommend corrective measures; and to determine the effects of landfilling on water quality. The water quality in the harbour is a result of the interactions of biological, chemical and physical processes in what was found to be a very dyanmic environmental system. Thus, changes in any one process will affect the harbour water quality; consequently, it is necessary to understand the processes and their interactions in sufficient detail if intelligent decisions are to be made.

Outline of Study

Extensive water quality surveys were carried out during 1972 and 1973. Various components of the harbour processes were examined using the survey data as a base. The study of each of these components formed the subject matter of a technical bulletin. A draft of these reports was reviewed by Ministry personnel and subsequently amended incorporating their comments.

Each of these bulletins appears as a separate section of this report. Some duplication of figures and tables obviously results, but this is necessary if the sections are to be self-contained. The sections are as follows:

A. Harbour Periodicities
B. Nutrient Trend Analysis
C. Iron-Phosphate Relationships
D. Dissolved Oxygen
E. Numerical Model
F. Bottom Fauna and Bacteriology
G. Heavy Metals and Pesticides
H. Survey Data

In this preface, the results of the study are summarized and merged to provide comprehensive statements concerning the water quality as related to the purposes of the study.

Several sources were used in the collection of the water quality data which form the basis of this report. Water and bottom sediment samples were obtained by conventional grab sampling techniques. Recording instrumentation (wind, water quality and current) was used to obtain time histories of physical properties and water quality. Bottom fauna samples and fish were collected. Historical water quality data were obtained from surveys conducted by the Hamilton Municipal Laboratories and the Ontario Water Resources Commission.

Discussion

Harbour Periodicities, Section A, discusses the periodic motions which affect the water quality sampling in several ways. Normally a sampling vessel moves to a location then sequentially takes water samples at the designated depths to provide the depth distributions of the water quality. Each sample must then be transferred to bottles for laboratory analyses with some onboard analysis of perishables and recording of results. The time required to cover all the stations in the grid was two to four days. In the harbour the principal discharges are along the south shore of the eastern end, consequently water movement is a big factor in the distribution of contaminants. If periodic motions are present sampling will be carried out for different circulation directions and patterns at different stations. If stratification is present, the thermocline will be displaced due to internal waves. As the epilimnion and hypolimnion have significantly different water quality characteristics, the depth of the thermocline is important for computing stocks. It is evident that the periodic motions in the harbour

affect the analyses and interpretation of water quality data.

If the periodic motions are to be modifying factors on the water quality survey results, it is necessary to know the length of these periods and causes of the motion in relation to the sampling times. Semi-diurnal periodicities (12 hr), Lake Ontario (5.5, 3.2, 2.4, 2.0 and 1.7 hr) and harbour (0.35 hr) oscillations were frequently observed in the chemistry and movements of both canal and harbour waters. The depth distributions of water chemistry in the region of the thermocline were significantly different between adjacent locations reflecting periodic wave activity. These periodic motions caused measurable variations in the water chemistry concentrations of up to 50 percent of the mean value recorded at a fixed point. This complicated the computation of nutrient (Section B), dissolved oxygen (Section D) and dissolved solid (used in the numerical model, Section E) stocks. Numerical efforts to synthesize a synoptic (data from all locations at same time) data set using the survey data available were only marginally successful. The problem was resolved by selecting a period when a nearly synoptic data set was available for the Numerical Model, October 4 and 5, 1972 (Section E) and using a mean value for the depth of the thermocline in the Nutrient Trend Analysis (Section B) and Dissolved Oxygen (Section D).

The exchange between the harbour and the lake was also found to be complex. In the absence of thermal stratification, alternating flows of lake water into the bay and bay water into the lake were observed. When thermal stratification is present, the usual mechanism of flow is an outflow of warm bay water above an inflow of cooler lake water; however, periods in which warm inflowing lake water overlies colder outflowing bay water, as well as alternting flows as described above, were observed. The canal may be regarded as a two layer dynamic flow system with the following properties:

1. currents from zero to 70 cm/sec are possible,
2. rapid changes at a given point of dissolved oxygen of 40 to 50 percent saturation and conductivity of 100 to 300 umhos can occur in a few minutes,
3. dissolved oxygen can have different time histories than temperature at a given point. This results from mixing of lake and harbour water of similar temperature at the layer boundaries,
4. time histories of both temperature and dissolved oxygen can be different between the two layers,
5. dissolved oxygen levels in the lower layer can be higher than the surface layer. At other times, near anoxic conditions can exist in the lower layer for extended periods of time.

The dynamic nature of the canal necessitated some approximation when utilizing these measurements in the Numerical Model (Section E). Velocity and concentration measurements at the two meter locations were simply averaged. Some time smoothing of the mass exchange in the canal was required for solution stability.

The measurements of discharges provided the basis for computation of mean values and the index of variation (standard deviation/mean) for the numerical model (Section E). Measurements of time variation of water chemistry and currents similarly defined the means and variations used in the Nutrient Trend Analysis (Section B) and Dissolved Oxygen (Section D). Validation of the continuous records was achieved by checking measured periodicities against theoretical computations. All chemical records were also validated by checking with standards and current meter records were verified by tracking drogues.

Nutrient Trend Analysis, Section B, discusses annual trends in nutrients and chlorophyll a concentrations, as well as the pathways of the nutrients and their relationships with chlorophyll a concentrations in the harbour. In general, the harbour was found to be eutrophic (annual mean chlorophyll a of 20 ug/l) with total phosphorus concentrations in the 40 to 200 ug/l range. However, no between year trend was observed in chlorophyll a for the period 1966 to 1972. Statistically relating chlorophyll a and total phosphorus concentrations showed a similar interdependence to that found in western Lake Erie. Due to the limited range of chlorophyll a and phosphorus concentrations in Hamilton Harbour, a limiting relationship between these parameters could not be proven. The region near the Ottawa Street slip has high levels of turbidity and total phosphorus with low chlorophyll a. In this region, productivity is considered to be limited by the available light. Measured total phosphorus concentrations in the harbour did not detect the storm water overflow even for survey days with large rainfalls. No statistical relationship could be found relating nutrient concentrations to rainfall.

Total phosphorus increased in mean annual concentration from 1968 to 1972 while ammonia levels dropped from 6.9 mg/l (Nitrogen) in 1970 to 1.7 mg/l (Nitrogen) in 1972. The ammonia concentrations are primarily a result of industrial loadings as the highest values were found in the epilimnion where most discharges are located even in the late summer and no natural peaking of ammonia was observed at overturn time. Total phosphorus also reaches maximum values in the epilimnion. Consequently, destratification (as examined in the Numerical Model, Section E) should reduce the nutrient levels in the photic zone. Nutrient removal would also reduce concentrations in the harbour.

The nitrogen loading to the harbour is approximately five times the harbour stock. Further computations indicate the importance of denitrification of nitrate, biological assimilation, absorption of ammonia by muds as well as the harbour-lake exchanges in the nitrogen pathways. As the phosphorus loading is approximately thirty times the harbour stock, chemical precipitation by iron and biological assimilation are important mechanisms in the control of phosphorus concentrations.

Iron-Phosphate Relationships, Section C, examines the solubility of phosphorus in the presence of iron. If the phosphorus is removed from the municipal discharge (as recommended in Section B) then iron will not be precipitated as ferric phosphate. However, iron will still be precipitated as ferric

hydroxide at pH greater than 4 and dissolved oxygen concentration above about 0.5 mg/l. Conditions favouring iron solubility are low pH, low dissolved oxygen and the presence of organic complexing agents.

The solubility of phosphorus is a function of biological activity, chemical form of phosphrous (orthophosphate, inorganic condensed phosphate, organic phosphate) complexing, hydrolysis kinetics and chemical equilibrium. Biological uptake and subsequent release are likely the most important processes in natural lake systems. Ferric ions precipitate phosphorus as ferric phosphate which is more soluble than ferric hydroxide at pH greater than 4 and calcium ions precipitate phosphorus as hydroxylapatite at pH greater than 6 and calcium hardness of 100 mg/l $CaCO_3$. If the iron loadings are reduced with the same phosphorus loadings, no change is theoretically expected in the phosphorus concentration due to hydroxylapatite precipitation. However, as the kinetics of precipitation are slow, some increase in phosphorus concentrations is likely to occur. If the phosphorus loadings are reduced with the same iron loadings the amount of absorbed phosphorus in the sedimented ferric hydroxide will be less but iron concentrations in the water will be unchanged.

Dissolved Oxygen, Section D, discusses the dissolved oxygen surveys in the harbour. A dissolved oxygen problem exists with large regions of the hypolimnetic waters at 5 mg/l or lower during the summer. This is below the Ontario standard of greater than 5 mg/l for fish, other aquatic life and wildlife. The survey results were interpreted to determine the most effective means of improvement. Since the dissolved oxygen levels are a result of the interactions of so many processes, it was decided that the discussion should be approached on the basis of stock available or deficit. Dissolved oxygen stock was calculated for the harbour using several methods. The harbour was divided into regions corresponding to each sampling station, and dissolved oxygen stock was calculated for the epilimnion and hypolimnion of each region from the mean concentrations in both layers at each station. Harbour wide means for each layer, and a grand mean for the entire harbour were also used to calculate stocks. During stratification, a system consisting of two separate layers results in a stock approximately 20 percent lower than that computed from mean depth values or mean harbour values. However, as only surface dissolved oxygen values are available from the earlier years, it was necessary to use the mean depth profiles. Dissolved oxygen depth profiles were generated and stocks computed by numerical integration of the profiles. The dissolved oxygen stock was higher in 1972 than 1966-70. This resulted from high surface dissolved oxygen, high water levels and high average wind speeds. Natural aeration and wind mixing were readily observable in the isopleths. Dissolved oxygen isopleths also indicate the photosynthetic activity and the sediment demand which is supported by the alkalinity isopleths. It is estimated that in August seasonal phytoplankton decay accounts for one-third of the deficit, with the remainder caused by chemical oxygen demand loadings and bottom sediments.

The worst dissolved oxygen deficits occur at the eastern end of the harbour near the Hamilton sewage plant, at the Ottawa Street slip and in the deeper waters. Reducing the chemical oxygen demand by 33 percent will decrease the dissolved oxygen deficit by 1.5 to 8 percent in August initially. To appreciate improvements of these magnitudes, one must average the dissolved oxygen stocks over 4 or 5 years as the variations between years due to natural phenomena are 3 or 4 times the annual improvement. Subsequent annual reductions in dissolved oxygen deficits will be functions of the sediment demand and trophic state. It is estimated that in 15 to 20 years the dissolved oxygen deficit will be a result of chemical oxygen demands only provided the trophic state is reduced to mesotrophic (Section B) and the sediments are oxidized (Section E).

Numerical Model, Section E, develops and tests the sensitivity of a two-dimensional time variant model which is capable of assessing changes in loadings and shoreline configuration. The model simulates transport and dispersion of contaminants. Measured time histories of winds and harbour-lake mass exchanges were used in the model. Unfortunately, time histories of loadings were not available. Thus the mean loadings for the principal discharges were calculated from historical daily records, intensive water quality surveys and recorded meter data. The effect of variations in industrial loadings was simulated by two separate runs of the model. One run used the mean loadings while a second run used the mean loadings plus one standard deviation. The sensitivities of the model to bottom friction, dispersion, wind direction, stratification, withdrawal, reductions in loadings, length of simulation period, and changes in geometry were evaluated. Most of the testing was for the October 4 and 5, 1972 data when a nearly synoptic water quality survey data set was available for validation.

The sensitivity of the water quality model to input variables in descending order of importance was:

1. wind speed and direction
2. geometry (as tested)
2. loading reductions of the order of 60 percent
2. stratification
3. loading changes of the order of 20 percent
3. harbour-lake mass exchange
4. dispersion
5. bottom roughness
6. withdrawals of the order of 2.3×10^6 m^3/day

Changes in the harbour geometry caused by the proposed industrial landfill would result in a reduction in harbour volume of approximately 5 percent. These changes have approximately the same LOCAL effect as a 20 percent increase in loadings. In other words, the filling shifts the LOCAL concentration contours approximately in the same manner as a 20 percent increase in loadings effected without filling. The filling by the Harbour Commissioners along the Burlington Skyway has resulted in water quality changes affecting approximately 15 percent more of the water area than if it had not been filled. However, only areas immediately adjacent to the new outfall locations deteriorated in excess of the Ministry's objective of no more than a 33 percent increase in dissolved solids.

Of the water quality enhancement techniques investigated, artificial destratification is the most attractive as it resolves the dissolved oxygen deficit in the hypolimnion, oxidizes the bottom sediments and reduces the accumulation of nutrients in the epilimnion. As the chemical oxygen demand loadings and bottom sediments make up approximately 66 percent of the oxygen deficit (Section D) reductions of chemical oxygen demand loadings of approximately 60 percent are expected to reduce the dissolved oxygen deficit in August by approximately 10 percent. This compares with an estimate of a reduction in dissolved oxygen deficit of 1.5 to 8 percent for a 33 percent decrease in chemical oxygen demand loadings based on oxygen stock computations (Section D).

Bottom Fauna and Microbiology, Section F, discusses the general benthic macroinvertebrate community in terms of species and density. It also compares the survey results of 1964-5 and 1972-3. Unlike the water quality characteristics in the harbour which are subject to the periodic nature of the harbour processes (Section A) the benthic community integrates to some extent the shorter period variations of water quality and sedimentation processes. As such it does provide a longer period mean. The benthic community in Hamilton Harbour has a low diversity (namely tubificidae "sludgeworms" with the odd midge and fingernail clam) and high density.

Toxic conditions exist in the southeast corner where six sediment samples were devoid of macroinvertebrates. Some changes were observed between 1964-5 and 1972-3. The region of sediments devoid of macroinvertebrates has shifted from the region adjacent to the Ottawa Street slip to the southeast portion of the harbour and the region is greater in extent. This change is accounted for by the shift in discharge of Hamilton sewage from the Ottawa Street slip to the primary sewage plant opened in 1964. The density of bottom invertebrates has also significantly increased since 1964-5. While the diversity of taxa is generally low, there appears to be a slight increase in the variety of taxa. In 1972-3, seven of the thirty-nine samples contained organisms other than worms, while only five of the 46 samples had the same properties in 1964-5. Live fingernail clams were also identified in the 1972-3 surveys, a taxon not found in 1964-5. The changes between 1964-5 and 1972-3 are indicative of a healthier biological environment and reduced toxicity possibly resulting from reductions in ammonia concentrations.

The microbiology survey in 1972 indicates that bacterial levels of coliforms, fecal coliforms and enterococcus are generally higher than those permitted for recreational waters where the geometric mean densities must be less than 1000, 100 and 20 per 100 ml respectively for at least ten samples per month. The highest regions of bacterial contamination exist in the regions of the sewage treatment plant outfalls and the principal industrial outfalls. There are no significant changes at the 95 percent significance level in the bacterial levels (geometric means) in the period 1970 to 1972. Data from the Hamilton Municipal Laboratory 1970 Annual Report indicate that the median values for total coliforms in the 1965-70 period are in general less than those in the 1960-4 period, and the median values in 1970 are substantially lower than 1969 with the exception of one sampling location. Thus, it can be stated that bacterial levels are generally lower than in 1969 or 1960-4 period.

Heavy Metals and Pesticides, Section G, discusses the collection of bottom sediments at eleven locations (for analyses of PCB, lead, chromium, cadmium, mercury and iron) and the analyses of fish muscle (for PCB, mercury and pesticides). High concentrations of heavy metals were found in the sediments particularly near Station 262 (where lead concentrations were 930 ppm, cadmium 18.5 ppm and mercury 1.7 ppm) and to a lesser extent, Station 257. The high heavy metals concentrations in the sediments support the suggestion in Section E (Numerical Model) that some bottom sediments should be removed. Such a removal, in addition to reducing oxygen demand, would remove heavily contaminated sediments.

Fish were netted in the northeastern and southeastern portion of the harbour. Only one White Bass with 0.51 ppm mercury in fish puree exceeded the maximum 0.5 ppm level considered suitable for human consumption. In general, mercury levels accepted as background concentration levels were found. PCB concentrations as high as 11.7 ppm were found in predator fish like White Bass or fish with high body fat like Goldfish. In general, the White Bass had PCB levels greater than 5 ppm. If the 5 ppm standard for DDT is used for PCB, a water quality degradation exists with unacceptable levels of PCB being present in fish. As the levels of DDT are small compared to the concentrations of breakdown products DDE and DDD recent DDT discharges to the harbour are unlikely.

Summary and Findings

Trophic State

The hypertrophic state (mean annual chlorophyll a 20 ug/l and total phosphorus 40 to 200 ug/l) of the harbour fails to meet the provincial objectives for fish and wildlife OR aesthetics and recreation. Annual nitrogen and phosphorus loadings are five and thirty times the stock of these nutrients in the harbour respectively, indicating the importance of chemical and biological removal in preventing increases in their concentrations. An analysis of the iron-phosphorus relationships in the harbour indicates that phosphorus removal will not cause significant increases in the iron concentrations. Total phosphorus and ammonia concentrations in the epilimnion during stratification are significantly higher than those in the hypolimnion, indicating that destratification would be beneficial.

Dissolved Oxygen

Dissolved oxygen levels below 5 mg/l exist in the lower portion of the hypolimnion for large regions of the harbour from July to September except during high wind conditions. These portions of the harbour do not meet the provincial criteria of greater than 5 mg/l for the protection of fish and wildlife. The areas in the deep portion, near the Hamilton WPCP, along the industrial south shore and at the western end have the largest oxygen deficits. It is estimated that approximately 66 percent of the deficit is caused by discharges and sediment demand and 33 percent by phytoplankton decay in August. A reduction in chemical oxygen demand loadings of approximately 66 percent will result in a reduction in deficit by about 5 percent in the first year. The sediment demand should be controlled by nutrient concentration reductions, oxidation and possibly selected sediment removal.

Landfilling

Landfilling is causing a measurable degradation of water quality in the region of the filling. Regions of the harbour adjacent to the outfalls will experience higher concentrations although only a very small portion will exceed the 33 percent increase limit defined as an objective for fish and wildlife. This problem can be relieved by ceasing to fill, improving treatment at the principal discharges and/or utilizing more harbour water for assimilation through the use of destratification.

Microbiology

Bacterial levels of coliforms, fecal coliforms and enterococci are generally higher than permitted for recreational waters. If this use is contemplated the sources of contamination must be determined and corrected. The storm water sewers are a likely source, however, it was not possible to correlate rainfall with higher concentrations of total phosphorus or nitrate during the 1972 surveys. (These chemical parameters are normally the most sensitive in urban areas and have been useful in other studies in identifying storm water overflows or bypasses.) It is considered that other sources are also contributing to bacterial contamination like industrial discharges or wildlife.

No change in bacterial levels was observed in the period 1970 to 1972.

Bottom Fauna

The surveys in 1972 and 1973 indicate a slight improvement in bottom fauna species in density and diversity from the 1964-5 survey. This may be related to reductions in ammonia concentrations. However, the region devoid of macroinvertebrate species has shifted with the lcoation of the Hamilton sewage treatment plant discharge. The toxicity existing in this region should be identified and corrected.

Heavy Metals in Sediments

Compared to other Great Lakes regions, high concentrations of lead, chromium, cadmium, mercury and iron were found in the sediments, particularly, in the Randles Reef area (location 262). The sources of heavy metal discharges should be identified and some action taken to reduce these loadings.

Pesticides, Mercury and PCB Levels in Fish

With the exception of one White Bass, mercury levels in fish puree were less than 0.5 ppm. Predator fish like White Bass had levels of PCB greater than 5 ppm and as high as 11.7 ppm which is considered an unacceptable level. This indicates PCB discharges exist and should be identified and controlled. DDT levels in fish puree are lower than the breakdown products DDE and DDD indicating that recent DDT discharges are not a problem.

Trends

Ammonia levels in the harbour have dropped from a mean value of 6.9 mg/l in 1970 to 1.7 mg/l in 1972 due to control measures. The bottom fauna macroinvertebrate community has improved slightly in density and diversity between 1964-5 and 1972-3. Although chlorophyll a concentrations have remained approximately constant since 1966, phosphorus concentrations have increased slightly since 1968. Oxygen demands due to bottom sediments have increased over the years and the dissolved oxygen deficits in the hypolimnion are presently a problem.

Recommendations

The following recommendations are based on the premise that much of the harbour waters can be brought to a water quality standard that will be suitable for fish, wildlife and recreation. These recommendations are arranged in order of priority to achieve the required water quality enhancement.

The hypertrophic state and dissolved oxygen deficits are the most pressing water quality problems. If the harbour is to support fish and aquatic life or meet the provincial standards for aesthetics and recreation, these problems must be rectified. As the problem will probably require 10 to 20 years to correct, it is important that these steps be undertaken as soon as possible. It is recommended that:

1. The concentrations of nutrients in the harbour be reduced by treatment.
2. The principal chemical oxygen demand loadings be reduced by approximately 60 percent.
3. Artificial destratification be considered as a means of reducing nutrient levels in the photic zone, oxidizing bottom sediments and preventing phosphorus from recycling.
4. Aeration of the hypolimnion and selective sediment removal be investigated as a means of reducing the sediment oxygen demand.

If the harbour is to support fish and wildlife, it is important that the causes of toxicity to bottom fauna in the southeast portion of the harbour and the sources of heavy metal and PCB contamination be identified and rectified.

The present levels of bacterial contamination do not meet the water quality criteria for recreational use. If this use is comtemplated for the harbour, the sources of bacterial contamination must be identified and rectified.

Landfilling is causing a local degradation of water quality. While the regions of the harbour affected by a degration which violates the provincial criteria for fish and wildlife are small, it is advisable to curtail landfilling with the existing water quality problems in the harbour.

Further Studies

Studies will be undertaken in 1974 to further amplify the findings of this report. As it is only possible to validate a two-dimensional numerical model in a dynamic system qualitatively, a three-dimensional model will be developed which will be validated by operating concurrently six installations, each consisting of one recording current meter and one water quality meter. The time histories of the major industrial outfalls will also be measured and incorporated into the model and a non-conservative will be modelled. The heavy metal sediment results will be analytically treated to relate sediment samples. As the oxygen demand of the sediments is important, sediment demands will be determined both in the laboratory and the field at key locations. Also, additional surveys will be undertaken to identify bacti sources.

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HAMILTON HARBOUR STUDY

section A

harbour periodicities

HAMILTON HARBOUR STUDY

SECTION A

HARBOUR PERIODICITIES

SUMMARY

AN INSTALLATION OF TWO AUTOMATIC DIGITAL RECORDING WATER CHEMISTRY MONITORS AND TWO CURRENT METERS HAS BEEN OPERATED IN THE BURLINGTON SHIPS CANAL AT APPROXIMATELY THE THIRD DEPTHS. THIS INSTRUMENTATION WAS SUPPLEMENTED WITH AN ANALOG DISSOLVED OXYGEN METER, AS WELL AS DIGITAL METERS OPERATED WITHIN THE HARBOUR.

THE DATA OBTAINED FROM THIS EQUIPMENT INDICATE THAT WATER MOTION IN THE HARBOUR AND CANAL IS A COMPLEX PHENOMENON. IN THE SHIPS' CANAL, ALTERNATING FLOW OF HARBOUR WATER TO THE LAKE AND LAKE WATER INTO THE HARBOUR WITH PERIODS OF 12, 5, 3.2, 2.4 AND 2.0 HOURS HAS BEEN OBSERVED, AS WELL AS SIMULTANEOUS OUTFLOW OF WARM HARBOUR WATER ABOVE LAKE WATER, AND EVEN OCCASIONAL FLOW OF LAKE WATER ABOVE HARBOUR WATER. THESE PERIODS ARE A RESULT OF SEMI-DIURNAL AND LAKE OSCILLATION EFFECTS, IN ADDITION, HIGH FREQUENCY VARIATIONS OF PERIODS 0.1-0.2 HOURS LIKELY DUE TO HARBOUR OSCILLATIONS HAVE BEEN OBSERVED.

AT ANY FIXED POINT IN THE HARBOUR, CURRENTS AND WATER QUALITY ARE A FUNCTION OF NOT ONLY WASTE DISCHARGES AND HARBOUR OSCILLATIONS, BUT ALSO LAKE-INDUCED MOTIONS. THESE MOTIONS PRODUCE TEMPORARY DISPLACEMENTS OF THE THERMOCLINE UP TO SEVERAL METERS FROM THE AVERAGE VALUE, CREATING DIFFICULTY IN OBTAINING SYNOPTIC SURVEY DATA BY CONVENTIONAL GRAB SAMPLING METHODS. THIS LIMITS THE VALUE OF PRESENTLY OBTAINED CHEMICAL DATA IN THE CALCULATION OF STOCKS AND OPERATION OF THE NUMERICAL MODEL, AND REQUIRES THE USE OF NUMERICAL AVERAGING TECHNIQUES IN THE USE OF SUCH DATA.

HAMILTON HARBOUR

HARBOUR PERIODICITIES

INTRODUCTION

The time variation of water movements and water quality in the harbour and ships' canal reflect changes of water levels, internal wave activity and photosynthetic related processes. These periodic variations are obviously important when interpreting harbour water quality.

To describe the harbour water quality, one would carry out a conventional boat sampling survey program. However, if the harbour is active with periodic variations of less than 4 hours during the survey, sampling at the various locations would be taking place in a random manner with respect to the periodicity of the processes. Evidence that this is occurring during a normal survey is the wide variation in the depth of the thermocline at different locations and isolated regions of higher or lower concentration which have no apparent cause. Consequently it is necessary to determine the magnitude of periodicity of water quality at locations in the harbour. Similarly if material balances are required for modelling or process analyses, it is necessary to know the magnitude and periodicity of the time variations of discharges and mass exchanges between the harbour and lake.

This section discusses the periodic variations of water chemistry and movement as measured by recording type meters. (The electro-chemical water measurements were supplemented by some intense grab sampling and laboratory analysis.) Records of the mass exchange in the ships' canal are used directly in the numerical model (section E) as a boundary condition. Spectral analysis of the data determines the principal periods and indentifies the most active processes. Cross correlating current and water chemistry measurements at the same and different locations establishes the spatial homogeniety and coupling of chemical and physical processes.

DESCRIPTION OF STUDY

Two recording chemistry (temperature, conductivity, dissolved oxygen and pH) and current meters (speed and direction) were operated in the Burlington ships' canal at approximately the third depths (3.6 and 6.7 meters from bottom). The meters were placed outside the boundary layer of the canal walls which was delineated by dye experiments. The meters nearer the water surface were supported by a bottom resting tower, while the others were attached to a submerged buoy. Water movements were measured with Plessey or Geodyne recording current meters and the water quality with Schneider "Robots" which were shore mounted and supplied by submerged pumps. Other equipment like a Hydro Products current

meter and Electronic Instruments Limited (E.I.L.) recording dissolved oxygen meters were used extensively. However, the full time depth distribution of movement and water quality concentration was not instrumented so that frequently the two locations could not provide a good estimate of harbour lake exchange mechanism. The four meter installation (with some supporting survey work) did reveal the complexity of the harbour-lake interchange. It also showed how conservative water quality measurements have additional features not present in the movement data (water quality distributions and movement patterns appear quite different). Adequate time series data were obtained for the numerical model which required integrated mean harbour-lake mass exchanges.

Recording current meters were also operated at 6.1 and 16.1 meters from the bottom for nearly two months in the harbour on 5 minute sampling during isothermal conditions (December to February). Analysis of the data showed the naturally occurring periodicities in the harbour so that these could be compared with water quality periodicities measured in the ships' canal and other harbour locations. These meters also provided a time history at depth at an interior location in the harbour for the numerical model, validating drougue findings and defining the range of variability.

A recording submersible water quality meter was used in the Ottawa St. slip, in conjunction with intense grab sampling to characterize the principal industrial discharges for the numerical model and process analysis.

All recording meters were checked with laboratory and field calibrations to provide reasonably accurate data. Time series analyses of the data and comparison with other measuring devices indicates whether the data series is valid. One expects certain natural frequencies to be present in the harbour and if different ones appear the data time scale may be suspect.

DATA ANALYSIS

The meters were set to record at various intervals from 5 to 20 minutes for currents and 10 to 60 minutes for water quality depending on the periods of interest. (Measurements must be taken at least double the frequency of interest.) Some analog records of currents and water quality were also taken in the ships' canal to provide continuous data. These analog measurements were obtained at the recording meter locations and operated simultaneously with the recording meters. Except for the shorter period (higher frequency) variation, the analog and digital measurements compared favourably.

Digital data was generally edited to remove erroneous readings and prewhitened using a running average technique with binomial smoothing coefficients (Jenkins and Watts, 1968). Chemistry data were detrended using a polynomial fitting technique where significant (Palmer and Izatt, 1970; Poulton and Palmer, 1973). Statistical analyses of the water quality and current data are presented in Tables

1-4 for the upper and lower canal locations and the Ottawa St. slip. Only periods of data which were validated by field calibrations and other checks are presented. All chemical parameters were tested for normal or log-normal distribution with time, using the Kolmogorov-Smirnov test (Poulton and Palmer, 1973). In general, non-normal distributions were obtained (probabilities <0.1). This is reasonable considering that the time variation of chemistry was mainly affected by lake-bay exchange processes and waste discharges. A few exceptions are indicated in Table 16.

Time series analytical methods were then applied to the smoothed data series to determine autovariance density spectra of water quality and current components (North is defined as along the axis of the canal). The statistical significance of the density concentrations was then determined after Jenkins and Watts (1968, p.82). The dissolved oxygen is presented in both concentration and percentage saturation which includes temperature effects. Cross correlations of water quality and currents at the same location and between water quality at both upper and lower locations were carried out (Ibid). The statistical significance of the coherences was estimated after Goodman (Panofsky and Brier, 1968. p. 158). Results of the time series analysis appear in Tables 5 to 11, and results of cross correlations appear in tables 12 and 13. Typical autospectra are plotted in figures 1 to 3 for chemistry and 4 to 6 for currents, and typical coherence spectra are plotted in figures 7 to 9.

EXPECTED PERIODS

Numerical solutions of the basic hydrodynamic equations have been used by Simpson and Anderson (1964), and Rockwell (1966) to obtain the expected oscillation periods of Lake Ontario. For the first two periods, Simpson and Anderson obtained 5.41 and 2.48 hr, while Rockwell obtained values of 4.91, 2.97, 2.15, 1.63 and 1.29 hr for the first five oscillation modes. By comparison, use of the Merian equation for oscillation in a closed rectangular basin yielded results of 5.85 hr (Rockwell, 1966) or 5.66 hr (Simpson and Anderson, 1964) for the first period. For Hamilton Harbour the predicted first mode, using the Merian equation, is 0.35 hr.

At the latitude (43° 18') of the ships' canal, the inertial period of circulation (Verber, 1966) is 17.5 hr. Inertial circulation has been observed in Lake Ontario near Pickering (Palmer, 1969; Weiler, 1968). The semi-diurnal astronomical tide has also been observed in the spectral analysis of Lake Ontario water level records (Hamblin, 1968). On the Great Lakes, tidal effects have also been observed at Green Bay and Escanaba (Johnson, 1963).

RESULTS

The variance density analyses are summarized in Tables 4 to 11 and Figures 1 to 6. Data from the upper meter location in the canal was more periodic particularly in May 1973. In general, the inertial period of 17.5 hr was not observed in the water chemistry with the exception of pH in October 1972 and September 1973. Semi-diurnal periodicities were observed in most water chemistry records particularly at the upper meter and at the lower meter in September and October 1972, a period of near isothermal conditions. The semi-diurnal periodicity in water

chemistry could be a result of waste discharges peaking at 0700 to 0900 and 1900 to 2100 hr, or tidal processes. There is some coincidence of the absence of semi-diurnal periodicity with last quarter in March 23-30, 1973, and first quarter in September 29-October 6, 1973. Strong semi-diurnal periodicity coincided with new moon or full moon during September 1972, and May, August and October, 1973, but as the semi-diurnal periodicity did not appear in all records, especially those at the lower depths, it is not possible to confirm the tidal source of semi-diurnal periodicity. The observed oscillation periods in the canal are compared with the theoretical values below:

Theoretical (HR) (Rockwell, 1966	Observed Canal Chemistry Upper	Observed Canal Chemistry Lower	Observed Canal Currents
4.9	5.0 to 6.0	5.3 to 7.5	5.5
3.0	3.0 to 3.4	3.1 to 3.7	3.2
2.2	2.2 to 2.5	2.5 to 2.8	2.3 to 2.9
1.6	1.9 to 2.1	2.0 to 2.2	
1.3	1.6 to 1.8	1.7 to 1.9	
-	1.35 to1.45	1.5 to 1.6	
-	1.2 to 1.3	1.2 to 1.4	

The observed periods are generally longer than the theoretical predictions which may be accounted for by friction (Rockwell, 1966). Some shorter periods are visible; although these may be higher longitudinal modes or transverse modes of oscillation, it is impossible to verify their nature.

In the harbour itself some of the periods observed in the canal are observed and are listed below:

Theoretical (HR) (Rockwell, 1966)	Observed Harbour Chemistry	Observed Harbour Currents Upper	Observed Harbour Currents Lower
4.9	4.0 to 6.0	4.3 to 5.0	5.5 to 6.0
3.0	2.5 to 3.5	2.6 to 3.2	2.4 to 2.9
2.2	2.0	2.3	2.2 to 2.4
1.6		1.7 to 1.9	1.7 to 1.9

Unlike the canal readings the harbour readings are influenced by both changing geometry and friction as well as possible periodic discharges, which will modify the periods. Nevertheless, the lake periodicities are present in the harbour in both the water chemistry and currents.

A significant variance density was frequently observed in the chemistry and currents in both the canal and harbour at 4 hours. The mechanism associated

with this period is unknown.

Periodicities associated with the harbour, which has a primary mode of 0.35 hr (Merian equation estimate) would require a sampling interval of 0.17 hr or approximately 10 minutes. From September 29 to October 6, the robots were operated at this interval. Periods of 0.43 to 0.45 hr (upper) or 0.46 to 0.50 hr (lower) and 0.36 to 0.38 hr may correspond to the primary and secondary modes of oscillation, with the difference between these values and the estimate being due to friction as well as the difficulty of estimating accurate modes for an irregular shaped water body like Hamilton Harbour. In addition, the analog records from the EIL meters operated in canal water (Figures 13 and 14) appear to have large amounts of white noise superimposed upon the longer period variations. The periodicities of this supposed white noise are for the most part 0.1 and 0.2 hr (too regular for white noise); these could be either a higher longitudinal or a transverse mode of oscillation for the harbour. Consequently many of the higher frequency variations of water chemistry reflect harbour oscillations. The numerous occurrence of these large oscillations undoubtedly affects any grab sampling program in the harbour.

CROSS CORRELATIONS

Coherence values and phase angles for all 5% significant cross correlations are presented in Table 12 for currents and chemistry at the same location in the canal, and in Table 13 for chemistry between the two levels of the canal. Typical coherence spectra are plotted in Figures 7 to 9.

For the most part, significant coherences between chemistry and currents reflect the semi-diurnal periodicity and the first few modes of lake oscillation (e.g Figure 7). Phase angle relationships are consistent with the fact that positive (to lake) currents are associated with harbour water of high conductivity as well as low pH and DO, and vice versa. These results verify the fact that the current and water chemistry recording meters are recording the same phenomena.

The existence of significant cross correlations between water quality parameters at the two levels in the canal is evidence for relatively homogeneous water most of the time between the levels of measurement. Thus the lack of significant coherences in August 1973 is a positive result, indicating that the two meters are measuring different water for much of this time period. This result is contrasted to that of September 29-October 6, where the coherence value is above the 5% limiting level for most time periods (Figures 8 and 9; data presented in Table 13 indicate periods of maximum coherence). These results are as expected from the fact that strong thermal stratification in the canal was present in August 1973 (6% difference between upper and lower mean temperature), but not during the period September 29-October 6 (0.5^{o} difference btweeen upper and lower mean temperature). Under such conditions, alternating flow of lake and harbour water past both intakes simultaneously predominates over the stratified situation present in August. The raw data from the robot monitors confirm this situation.

DISCUSSION

In most robot monitor data, the chemical characteristics of lake and harbour water could easily be identified. Figure 10 shows some data obtained during the period April 30-May 28, when very strong 12, 5 and 3.2 hour periodicities (Table 7) were observed for all parameters. The parameters were strongly intercorrelated, as would be expected for alternating flow of lake and harbour water past the robot intake. Typical ranges of values observed for lake water were: temperature, below 10°C; DO, 12-15 mg/l; pH, 7.6-8.0 units; and conductivity, 300-450 umhos. For harbour water, typical values were: temperature, above 10°C, DO, 8-12 mg/l, pH, 7.0-7.6 units; and conductivity, 500-650 umhos.

Similar intercorrelation of temperature and DO is visible in September 1973 data from the upper EIL dissolved oxygen meter, presented in Figure 11. Conductivity and pH data were intercorrelated in a similar fashion to the May data, although observed changes in conductivity were small in extent. Typical conductivity values were 300-400 umhos for lake water and 400-500 umhos for harbour water. The decreasing trend of harbour water conductivity as the year progresses is in agreement with results of the 1972 surveys. It is also reflected in the mean conductivity values in Tables 1 and 2; the decreasing difference between lake and harbour water conductivity is reflected in the decreased standard deviations.

Results obtained with the EIL dissolved oxygen probes indicated that the lake-harbour exchange mechanisms were much more complicated than indicated by the robots, even when operated at a 20 minute sampling interval. Some of the conditions observed were as follows:

1. Dissolved oxygen and temperature at times are strongly intercorrelated (Figure II, as mentioned above).

2. Dissolved oxygen and temperature can have different time histories (Figure 12). At the same time conductivity and pH had a similar time history to DO. This resulted from alternating flow of lake and bay water of similar temperature (see also point 6 below).

3. Considerable high frequency variations of both temperature and dissolved oxygen frequently occurs (Figures 13 and 14). The extent of such variation is much more pronounced at the upper level (see especially Figure 14), although the time history of lower frequency changes may be different at the two levels (Figure 13).

4. The dissolved oxygen concentrations at the lower level can be higher than that at the upper level (Figure 14), as a result of lake water (colder, higher DO) occurring below harbour water, in agreement with thermal wedge studies (Dick and Marselek, 1972).

5. Periods of near anoxic conditions lasting for as long as 3 days have been observed at the lower level (Figure 15). The length of record for such conditions was limited by a power failure; had this not occurred, the low DO would have been seen for much longer. This behaviour was in direct contrast to that observed in Figure 14, and was confirmed by several Winkler titrations. Means and standard deviations for two days' data at this time were 5.9 ± 1.9 mg/l for the upper level and 1.8 ± 1.1 mg/1 for the lower level.

6. It is possible for reversed flow conditions to occur (inflowing lake water above outflowing bay water). These conditions were sustained for more than 8 hours in the morning of August 20, 1973, when typical conductivity values were 370 umhos at the top and 460 umhos at the bottom. pH values were 7.7 at the top and 7.0 at the bottom. As the water temperature at the top was above 21°C, and that at the bottom was about 16°C, this respresented an outflow of hypolimnetic bay water under an inflow of epilimnetic lake water. On August 19, these conditions alternated with an outflow of bay water at both levels, combining to produce the result depicted in Figure 16 for temperature and conductivity and Figure 12 for dissolved oxygen.

That the installation of current and water chemistry meters at two fixed depths is inadequate to describe the entire flow situation, is shown by two series of depth profiles of conductivity and temperature, obtained July 11, 1973 (Figure 17). At 0945, a gradual stratification, both thermal and chemical, occurred mostly between the depths of the two water chemistry meter intakes. On the other hand, at 1600 hours, both intakes were sampling lake water while bay water was limited to less than 3 meters depth at the surface. This simple illustration shows the large range over which the thermocline can vary in a matter of a few hours.

These observations show that flow through the canal is an exceedingly complex phenomenon. Complete description of mass exchange between the lake and harbour would require instrumentation at a number of closely spaced depth intervals, a prohibitively expensive requirement. The data obtained, however, should provide a reasonable description of mass exchange within the limitations of the numerical model.

A 24 hour intensive sampling survey was conducted on July 10-11, 1973, at station 251 (far east end of the harbour, about 1 km south of the ship canal). Temperature, DO, pH and conductivity were measured every 2 hours at a depth of 3 meters. The results, presented in Table 14 and Figure 18, show that pH and DO have a diurnal relationship as expected for photosynthesis. High DO and pH, due to CO_2 consumption, are observed in the daytime, followed by decreased DO and pH at night due to respiration. Increased HCO_3 content may also play a part in the maximum conductivity observed at sunrise. The effect of the canal is not seen at this point, with the coefficients of variation of conductivity being 5%, compared

to values of 8 to 15% observed in the canal (Tables 1-2). Lake-induced periodicities are also absent in these figures. The winds were generally light (1.8 to 6.7 m/sec.) and mainly from the north and west (Table 15) during this survey. The small variations in the conductivity suggest the importance of the wind in the distribution of a contaminant in the harbour as it is known that the principal waste discharges have indicies of variation of 4 to 20 percent.

CONCLUSIONS

Observed water quality and current meter data indicate that water motion in the harbour and ship canal is a complex phenomenon. In the ship canal, alternating flow of harbour water to the lake and lake water into the harbour with periods of 12, 5, 3.2, 2.4, 2.0 hours have been observed, as well as simultaneous outflow of warm harbour water above inflowing lake water, and even occasional flow of lake water above harbour water. The boundary between the water layers can vary tremendously with time (e.g. Figure 17). In addition, high frequency variations of periods 0.1-0.2 hr likely due to harbour oscillations have been observed.

At any fixed point in the harbour, currents and water quality are a function of not only harbour discharges and oscillations, but also lake-induced motions. These various motions result in temporary displacements of the thermocline up to several meters from the average value. Such phenomena create difficulty in performing an adequate synoptic sampling survey by conventional grab sampling means. As synoptic data are required for accurate calculation of nutrient and dissolved oxygen stocks, as well as for operation of the numerical model, these considerations must be accounted for in designing a sampling survey, as well as in the use of results of existing surveys. Numerical methods of data averaging (see, for example, Section D, dissolved oxygen trend analysis) provide a partial solution to these difficulties, and improved techniques in this field should prove valuable.

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TABLE 1

Means and Standard Deviations of Water Chemistry Data in the Burlington Ship Canal

Upper meter (6.7 m from bottom)

Time Period	# of Readings	Temperature (°C) Mean	Temperature (°C) SD	Dissolved Oxygen mg/l Mean	Dissolved Oxygen mg/l SD	Dissolved Oxygen % Sat. Mean	Dissolved Oxygen % Sat. SD	pH Mean	pH SD	Conductivity (umhos/cm at 25°C) Mean	Conductivity (umhos/cm at 25°C) SD
1972 Sept. 12-24	280	19.6	1.8	7.6	1.6	82	17	7.6	0.1	469	41
Oct. 6-12	146	18.5	5.0	8.0	1.5	84	15	7.3	0.4	452	53
1973 Mar. 23-30	480	5.4	0.8	10.9	1.8	87	12	6.5	0.2	600	49
Apr. 10-24	1008	-	-	11.7	0.9	-	-	7.1	0.2	588	68
Apr.30-May 28	1980	12.3	2.0	10.6	1.6	98	12	7.4	0.2	560	83
Jul. 9-20	877	15.6	1.7	8.0	2.0	91	26	7.5	0.2	469	53
Aug. 12-20	576	17.6	2.6	7.0*	2.0*	73*	20*	7.5	0.3	432	42
Sept. 12-24	859	14.9	2.1	7.8*	1.6*	76*	15*	7.5	0.2	421	32
Sept. 29-Oct.6	982	16.5	0.6	6.9*	1.2*	70*	12*	7.5	0.2	427	32
Oct. 17-28	789	13.1	1.3	6.8*	1.0*	64*	9*	7.3	0.2	427	29

Note: *Analog DO data from EIL meter was digitized and processed for these time periods.
Temperature data in April was invalidated by slowly responding digitizer action.
DO (% sat.) invalid as this is calculated from temperature.

TABLE 2

Means and Standard Deviations of 1973 Water Chemistry Data in the Burlington Ship Canal

Lower meter (3.6 m from bottom)

	# of	Temperature		Dissolved Oxygen				pH		Conductivity	
	Readings	(°C)		mg/l		% Sat.				(umhos/cm at 25°C)	
Time Period		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1972 Sept. 12-14	280	19.4	1.5	8.0	1.0	86	10	7.8	0.2	405	33
Oct. 6-12	139	17.9	1.4	7.6	1.1	79	12	7.5	0.3	453	45
1973 Mar. 23-25	108	3.3	0.9	12.2	0.4	92	4	7.0	0.4	554	66
Jul.25-Aug.7	936	13.9	2.9	-	-	-	-	7.7	0.3	415	67
Aug. 10-21	744	11.8	4.0	7.7*	3.9*	70*	34*	7.6	0.5	399	39
Sept. 7-12	350	9.1	1.1	10.3	0.4	89	3	7.6	0.3	332	8
Sept.26-Oct.6	1274	16.0*	0.5*	7.3*	1.4*	73*	14*	7.7	0.3	408	43
Oct. 6-17	784	14.6*	2.6*	6.7*	1.6*	65*	14*	7.5	0.2	405	45
Oct. 17-29	847	9.6*	2.3*	8.8*	1.9*	76*	15*	8.0	0.3	365	34

Note: *Analog temperature and DO data from EIL meter was digitized and processed for these time periods.
DO electrode was not functioning properly in July.

TABLE 3

STATISTICAL SUMMARY OF CURRENT METER OPERATIONS
BURLINGTON SHIP CANAL

Location Code	Period of Operation 1972		No. of Readings	Time Interval	Max. Speed	Avg. Speed	Percentage of Time Currents Going Towards	
	From	To		Minutes	cm/sec	cm/sec	Harbour	Lake
11101 (upper)	Sep. 11	Sep. 24	1844	10	45.1	9.4	34	32
11101 (upper)	Sep. 28	Nov. 2	5045	10	122.7	10.6	34	48
11102 (upper)	Nov. 3	Nov. 10	1032	10	42.6	13.9	18	44

TABLE 4

RECORDING CHEMISTRY METER
OTTAWA ST. SLIP
FEBRUARY 2-15, 1973

	Temperature °C	Dissolved Oxygen		Turbidity, FTU
		mg/l	% sat.	
Mean	10.4	8.6	77	30
Std. Dev.	1.6	0.7	8	5
Periodicities	6.0	4.0	4.0	4.0
(hours)	3.5		2.5	
		2.0	2.0	2.0

TABLE 5

PERIODICITIES IN HOURS OBSERVED DURING SEPTEMBER 1972
IN THE BURLINGTON SHIP CHANNEL

Location	Temperature	Dissolved Oxygen mg/l	Dissolved Oxygen % Sat.	pH	Conductivity	Currents North	Currents East
Upper	* 24			24			
6.7 meters from		12	12	12	* 12	* 14	12
bottom	6.0	** 5.5	** 5.5	6.0	* 5.0	* 5.5	6.7
	4.0	4.0				4.3	4.3
			* 3.3	3.2	* 3.3	* 3.2	2.9
						2.3	2.5
Lower		12		* 14	15		
3.6 meters from	6.0			6.0	6.7		
bottom			5.0				
	3.2						

Note: All periods are stated in hours
Statistically significant peaks are indicated by: * for 80% Confidence
** for 95% Confidence
Current meter directions are rotated so that north is along the channel
The lower current meter did not function properly in this period

TABLE 6

PERIODICITIES IN HOURS OBSERVED DURING OCTOBER 1972
IN THE BURLINGTON SHIP CANAL

Location	Temperature	Dissolved Oxygen		pH	Conductivity	Currents	
		mg/l	% Sat			North	East
Upper	* 24			* 18	24		30
6.7 meters			12			14	
from bottom	9				7.5		7.5
	5.5	5.5		5.5	5.0-5.5	5.0	5.0
							4.0
	3.0	3.3	3.3	3.5	** 3.3	** 3.2	3.0
						** 2.3	2.1
Lower					* 24		
3.6 meters		* 12	12	14			
from bottom		6.7	6.7	7.5			
				5.0			
	3.7	3.5	3.5	** 3.1	3.3		

Note: All periods are stated in hours
Statistically significant peaks are indicated by: * for 80% Confidence
** for 95% Confidence
Current meter directions are rotated so that north is along the channel
The lower current meter did not function properly in this period.

TABLE 7

PERIODICITIES IN HOURS OBSERVED DURING
SPRING 1973 IN THE HAMILTON SHIP CANAL (Upper meter)

Dates	Temperature	Dissolved Oxygen mg/l	Dissolved Oxygen % Sat.	pH	Conductivity
Mar. 23-30	* 24.				
	* 5.3	6.0	6.0	5.3	5.3
	3.2	3.2	3.4	3.4	* 3.2
	2.2	* 2.4	2.4	2.4	2.4
	1.9	* 2.1	2.1	* 2.0	2.1
	1.60	1.66	1.63	1.60	1.60
	1.33	1.41	1.43	1.37	1.33
April 10-24					** 12
		5.3			* 5.3
		** 3.2		** 3.2	** 3.2
		2.5		2.3	2.4
		2.0			
		* 1.60		1.60	1.71
		* 1.37		1.33	1.30
April 30-May 28	* 12.	* 12.	* 12.	12.	** 12.
	** 5.0	** 5.0	** 5.0	** 5.0	** 5.0
	** 3.2	** 3.2	** 3.2	** 3.2	** 3.2
	2.5			2.5	2.5
	* 2.0			2.1	
	1.60	1.8		1.55	1.55

Notes: All periodicities are stated in hours.
Temperature and DO (%) data not presented for April due to invalid data on tape.
All data presented are for the upper location (6.7m from bottom); the lower meter did not function properly during this time period.

TABLE 8

PERIODICITIES IN HOURS OBSERVED DURING
AUGUST 1973 AT THE BURLINGTON SHIP CANAL

Date & Location	Temperature	Dissolved Oxygen mg/l	Dissolved Oxygen % Sat.	pH	Conductivity
Lower	4.8				6.0
3.6m from				4.0	
bottom	3.5				3.2
July 25-Aug. 7	2.7			2.5	* 2.6
	2.2				
	1.85			1.85	* 1.78
	1.60				* 1.60
	1.33				* 1.33
Upper	* 24				
6.7 from		* 13	* 13	* 13	14
bottom		5.5	* 5.3	* 5.3	** 5.3
Aug. 12-Aug. 20	4.0			4.0	
	3.2	3.2	3.2	3.2	
	* 2.4	* 2.4	* 2.4	* 2.4	* 2.3
	* 2.0				2.0
	* 1.60	* 1.71	* 1.71	1.66	1.66
	1.41	1.45	* 1.45	* 1.41	* 1.41
	1.23			1.2	1.23
	1.12				
Lower	24				
3.6m from	9.6				12
bottom	5.3			6.0	
Aug. 10-Aug. 21		* 4.4	* 4.4		3.7
	2.5	* 2.5	** 2.5	* 2.8	* 2.5
		2.0	2.0	2.1	
	1.85	1.78	* 1.78		* 1.85
	1.60			* 1.60	** 1.66
	1.41			1.30	1.33
					1.19

Note: Dissolved oxygen sensor not functioning in July 25-Aug. 7 period.
Statistically significant peaks indicated by : * for 80% Confidence Level
** for 95% Confidence Level

TABLE 9

PERIODICITIES IN HOURS OBSERVED DURING
SEPTEMBER 1973 AT THE BURLINGTON SHIP CANAL

Data and Location	Temperature	Dissolved Oxygen mg/l	Dissolved Oxygen % Sat.	pH	Conductivity
Upper	12	12	12	16	12
6.7 from	5.3	** 5.3	** 5.3	** 5.3	** 5.3
bottom	3.0	** 3.2	** 3.2	** 3.2	** 3.2
Sept. 12-24	2.3	* 2.4	2.4	* 2.4	* 2.4
	2.0	2.0	2.0	* 2.0	2.0
	1.60	* 1.71	* 1.71	* 1.71	1.71
	1.41	1.50	1.50	1.45	1.41
				1.26	1.26
Lower					13
3.6m from				4.4	
bottom		2.7		3.3	
Sept. 7-12	2.4	2.1	2.1		* 2.4
	1.6			1.6	1.5
	1.4				
		1.2			1.0
Upper					
6.7m from		4.4	5.0	5.0	4.4
bottom	** 3.1	* 3.3	* 3.3	* 3.3	* 3.1
Sept. 29-Oct. 6	2.4		2.5	2.5	2.5
		2.0	2.0	2.0	2.0
	1.8			1.67	
		1.54	1.54		
			1.38		
	1.25	1.25	1.25	* 1.25	* 1.25
	0.56			0.56	
	0.45	0.43	0.43	* 0.45	* 0.45
	0.36				0.37
Lower	4.4				4.4
3.6 from	3.1	* 3.6	* 3.6	*3.3	* 3.3
bottom				2.5	2.5
Sept. 29-Oct. 6					2.1
	1.74	1.74	1.74		
	1.54	* 1.48	1.48		1.54
	1.29	1.21	* 1.21	1.25	1.25
	1.11	1.08			1.11
	0.71			* 0.67	
	0.59				
		0.48	0.48	* 0.46	0.50
	0.38				* 0.37

Note: Statistically significant peaks indicated by: * for 80% confidence level
** for 95% confidence level

TABLE 10
PERIODICITIES IN HOURS OBSERVED DURING
OCTOBER 1973 AT THE BURLINGTON SHIP CANAL

Date and Location	Temperature	Dissolved Oxygen mg/l	Dissolved Oxygen % Sat.	pH	Conductivity
Lower		* 12	* 12	* 12	** 12
3.6m from	** 5.3	** 5.3	** 5.3	5.3	** 5.3
bottom		3.2	* 3.2	* 3.2	3.2
Oct. 6-17	* 2.7				
	** 2.2	2.2	2.2	2.0	2.2
	* 1.71	1.71	1.71	1.78	1.85
	1.50			1.41	1.45
Upper		** 12	** 12	*12	*12
6.7m from	5.3	5.0	* 5.0	5.3	5.3
bottom	3.2	* 3.2	* 3.2	3.2	3.2
Oct. 17-28			2.3	2.5	2.5
	1.78	* 1.78	* 1.78	* 1.78	* 1.78
	1.45	1.45	1.45		1.39
		1.28	1.28	1.33	
	1.07	1.07	1.07		1.03
Lower		* 12	* 12		12
3.6m from	5.3	5.0	5.0	5.0	5.3
bottom	3.2	3.2	3.2	3.2	3.2
Oct. 17-28	1.88	1.78	1.78	1.78	
	1.45		1.52		
		1.25	1.28	1.19	1.25
	1.07	1.07	1.07	1.07	1.03

Note: Statistically significant peaks indicated by: * for 80% confidence level
** for 95% confidence level

TABLE 11

HAMILTON HARBOUR

MAJOR SPECTRAL PEAKS (HOURS)

Auto Spectra of Currents
(80% Confidence Level)

Location & Period	North-South	East-West
113 DEC 72	8.6*, 4.0*, 2.9, 2.3 1.9, 1.5, 1.1	5.5*, 2.4, 1.3
114 DEC 72	12.0, 5.0*, 4.0*, 2.6*, 1.5*, 1.3	3.2, 2.0, 1.7* 1.5, 1.2*, 1.1*
113 JAN 73	6.0*, 2.7*, 2.2, 1.4*, 1.2*	2.4, 1.7*, 1.3, 1.2
114 JAN 73	4.3*, 2.3, 1.9, 1.15,	6.7, 4.0, 1.9, 1.5, 1.1

*95% Confidence Level

TABLE 12

SIGNIFICANT CROSS CORRELATIONS BETWEEN
WATER CHEMISTRY AND CURRENTS, BURLINGTON SHIP CANAL

Date	Location	Dissolved Oxygen mg/l N	Dissolved Oxygen mg/l E	Dissolved Oxygen % Sat. N	Dissolved Oxygen % Sat. E	pH N	pH E	Conductivity N	Conductivity E	No. of Data Points
Sept 12-24 1972	Upper	None	None	7.5(130) 5.5(121)	None	12(-146) 5.5-6(170) 3(163)	None	12-15(7) 5.5-6(3) 3.2(-76)	2.6(137)	280
Oct 6-12 1972	Upper	5.0(-172) 3.3(138)	None	5.0(-166)	None	None	None	5.0(4) 3.0-3.3(50)	None	146
July 9-20 1973	Upper	None	None	None	None	5.0(-142)	None	5.0(12) 3.3(3) 2.2(-15)	None	877
Aug 12-20 1973	Upper	12(-154) 5.0(-168) 2.3(86) 1.7(48)	None	12(-156) 5.0(-168) 2.3(87) 1.7(52)	5.7(164)	5.0-5.7(-154) 3.1(148) 2.1(100) 1.2(-76)	5.0-5.7(-172)	5.0-5.7(21)	None	576

Notes: Indicated figures are the periods in hours for 5 percent significant coherences (Panofsky & Brier, 1968), followed by the phase angle in degrees.
N and E are north and east currents, respectively. Current directions have been rotated so that north lies along the channel.

TABLE 13

SIGNIFICANT CROSS CORRELATIONS OF WATER CHEMISTRY
BETWEEN UPPER AND LOWER LEVELS, BURLINGTON SHIP CANAL

Date	Temperature	Dissolved Oxygen mg/l	Dissolved Oxygen % Sat.	pH	Conductivity	No. of Data Points
Sept. 12-14, 1972	12 (-12)	3.2 (-5)	none	12 (-22)	12 (-3)	280
	3.0 (-24)			5.0 (-1)	5.5 (12)	
				2.2 (27)		
Oct. 6-12, 1972	none	15 (1)	15 (-9)	none	6.0 (-1)	139
		2.6 (54)	3.3 (22)		2.5 (6)	
			2.7 (11)			
Aug. 12-20, 1973	none	none	none	none	none	576
Sept. 29-Oct. 6, 1973	9 (-6)	12 (5)	12 (7)	12 (2)	12 (8)	327
	3.1 (-17)	4.0 (-18)	4.0 (-18)	4.4 (-11)	3.2 (-3)	
	2.1 (19)	2.3 (-22)	2.3 (-28)	3.4 (1)	2.5 (-6)	
	1.7 (-2)	1.6 (-4)	1.6 (5)	2.7 (7)	2.1 (0)	
	1.25 (-15)	1.38 (-35)	1.38 (-42)	1.7 (29)	1.7 (15	
	1.11 (3)	1.25 (-15)	1.21 (-14)	1.25 (-8)	1.25 (-25)	
		1.11 (-7)	1.11 (-11)		1.08 (-9)	
Oct. 17-Oct. 29, 1973	12 (-2)	12 (11)	12 (14)	12 (13)	12 (9)	789
	6.4 (-38)	5.0 (-13)	5.0 (-14)	5.0 (-7)	5.0 (-2)	
	3.0 (-23)	3.2 (-8)	3.2 (-4)	3.0 (2)	3.2 (15)	
		1.8 (21)	1.8 (23)			

Note: Indicated figures are the periods in hours for 5% significant coherences (Panofsky & Brier, 1968), followed by the phase angle in degrees.

TABLE 14

24 HOUR HAMILTON HARBOUR WATER CHEMISTRY
(GRAB SAMPLING 10 AND 11 JULY 1973)

TIME	TEMP. DEGREES CENT.	DISSOLVED OXYGEN mg/1	COND. AT 25 DEGREES umhos/cm	pH
1445	25.3	7.8	580	8.2
1645	24.8	9.0	622	8.5
1845	24.6	9.0	592	8.2
2045	24.3	8.9	558	7.7
2255	23.0	1.5	610	7.5
0055	24.0	6.3	594	7.4
0305	23.7	6.8	635	7.6
0500	24.2	6.1	645	7.5
0705	23.0	6.2	687	7.5
0940	22.0	5.9	580	7.7
1110	22.0	6.5	635	8.0
1320	21.8	7.6	610	8.1
Mean	23.5	7.3	612	7.8
St. Dev.	1.2	1.2	35	0.4
Index Variation	4%	16%	5%	4%

TABLE 15

WIND AND WATER LEVEL CLIMATE

10 AND 11 JULY 1973

		WIND		WATER
		Speed M/Sec.	Dir.	LEVELS M
July 10	0900	3.1	W	75.447
	1100	1.8	W	.426
	1300	4.0	W	.456
	1500	4.9	W	.456
	1700	4.9	NW	.417
	1900	4.0	N	.447
	2100	3.6	NW	.417
	2300	2.7	NW	.395
July 11	0100	2.2	NW	.426
	0300	2.2	NW	.408
	0500	2.7	N	.426
	0700	4.0	N	.408
	0900	6.7	N	.417
	1100	5.8	N	.417
	1300	5.4	NW	.426
	1500	6.3	NW	.426

TABLE 16

CHEMICAL PARAMETERS WITH
SIGNIFICANT PROBABILITY OF
NORMAL OR LOG-NORMAL DISTRIBUTION
HAMILTON SHIP CANAL, 1973.

Date	Location	Parameter	Distribution	Probability
Mar. 23-30	upper	temperature	log-normal	0.498
July 9-20	upper	conductivity	normal	0.953
Sept. 7-12	lower	temperature	log-normal	0.549
Oct. 17-28	upper	dissolved oxygen	normal	0.406

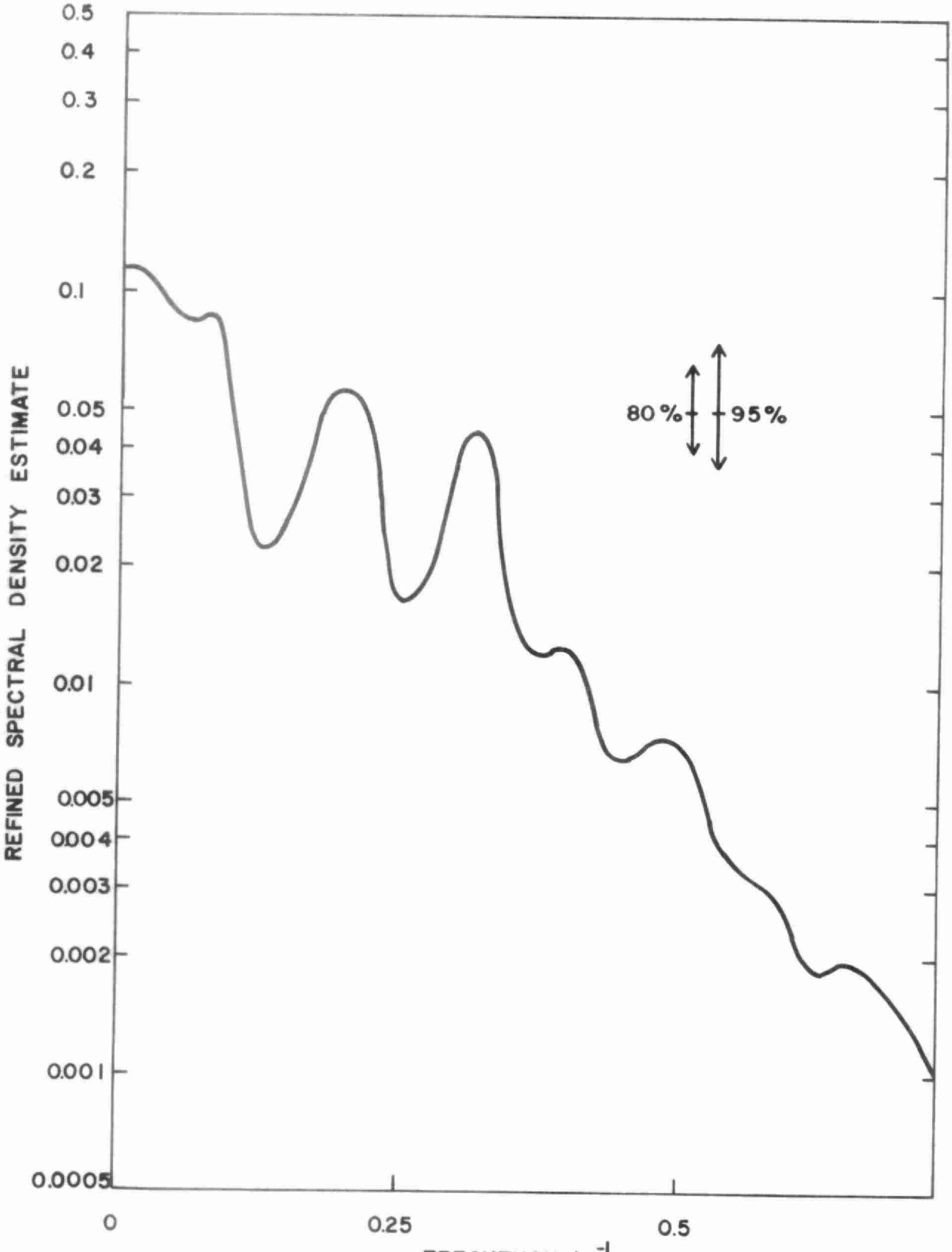

FIG. I AUTOSPECTRA FOR PH. APRIL 30-MAY 28, 1973 BURLINGTON SHIP CANAL, UPPER LOCATION 6.7 M. ABOVE BOTTOM

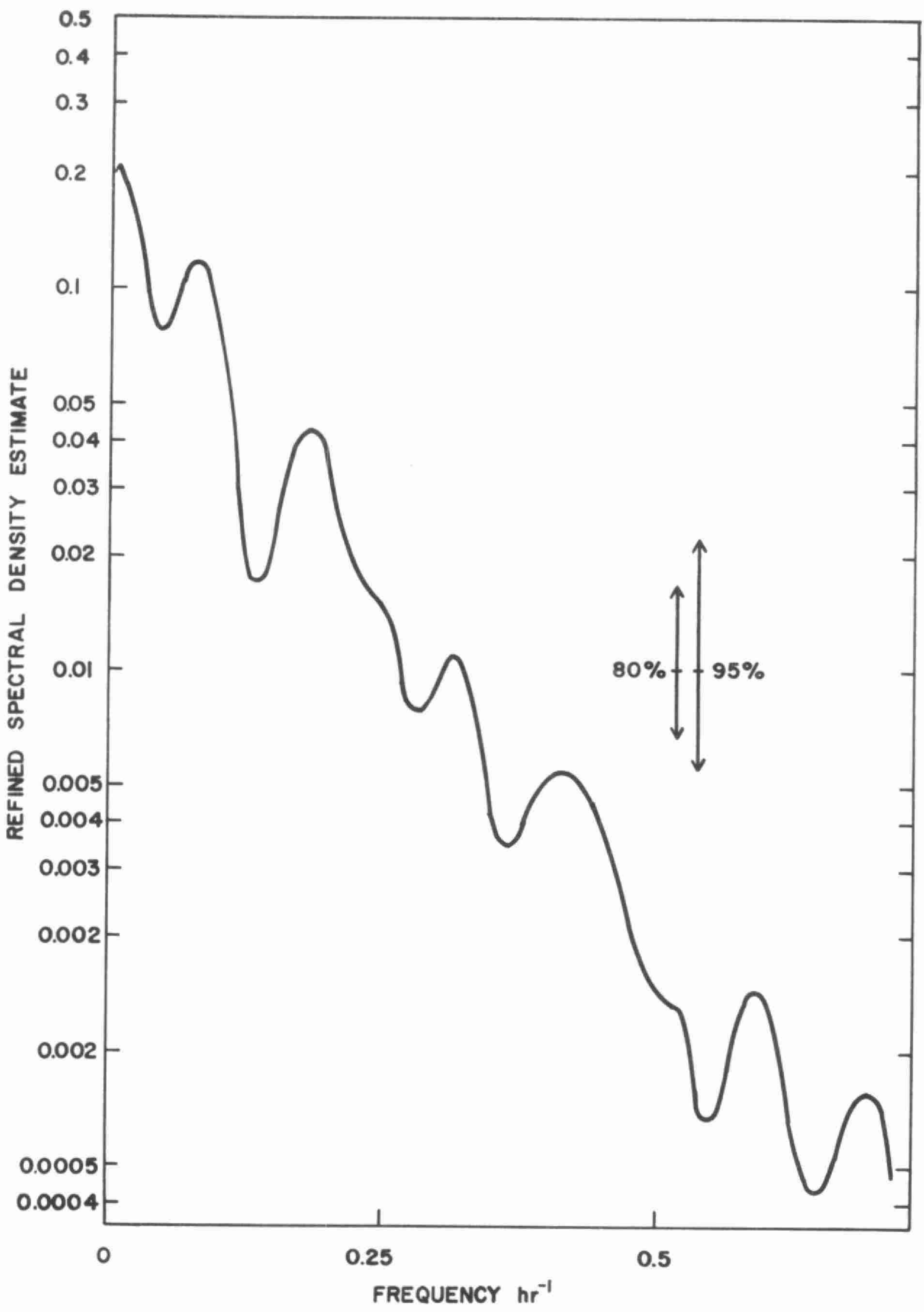

FIG. 2 AUTOSPECTRA FOR DISSOLVED OXYGEN (% SATURATION) AUGUST 12-20, 1973 BURLINGTON SHIP CANAL, UPPER LOCATION 6.7 M ABOVE BOTTOM

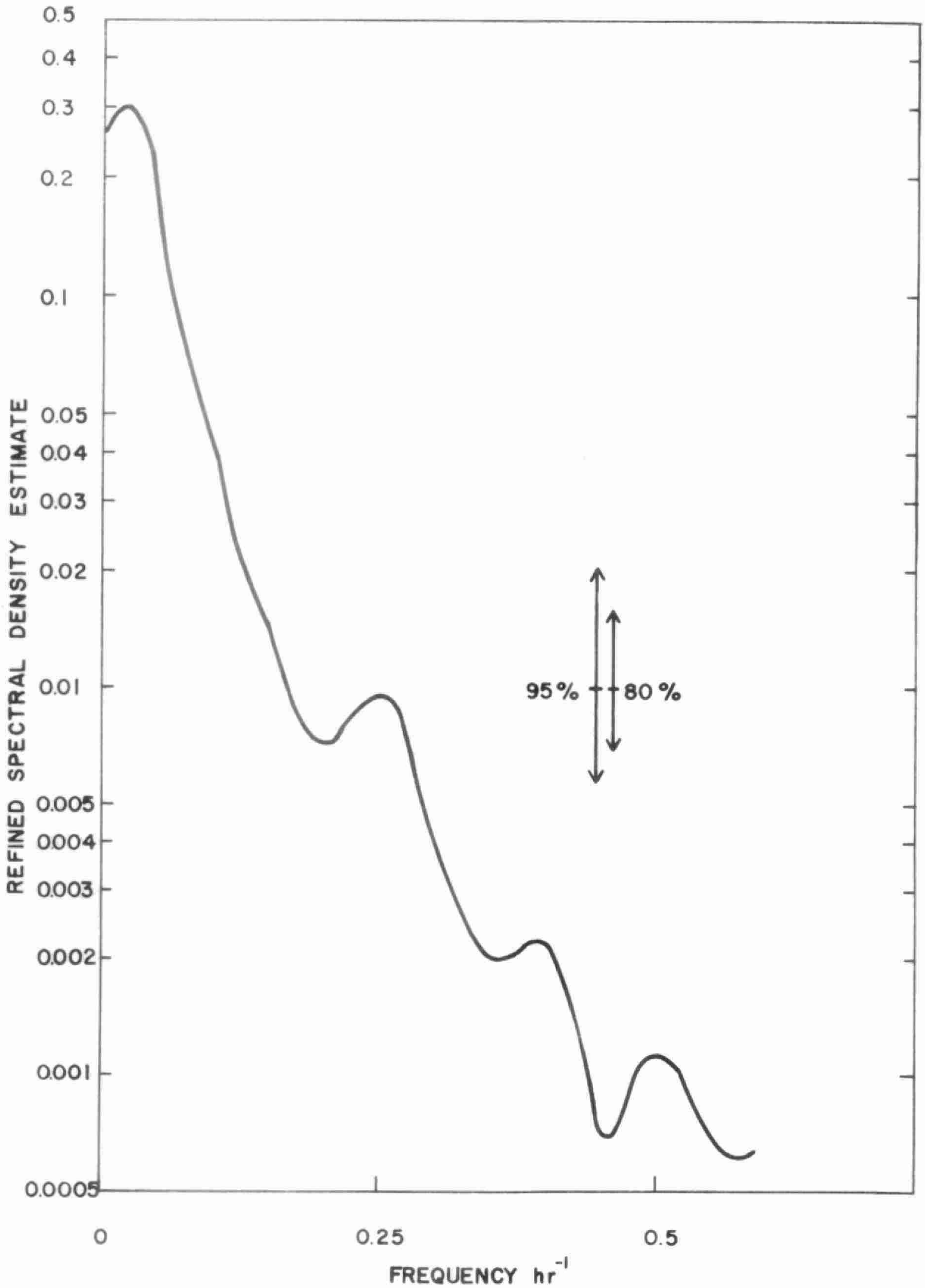

FIG. 3 AUTOSPECTRA FOR DISSOLVED OXYGEN (% SATURATION) RECORDING CHEMISTRY METER OTTAWA ST. SLIP, 0.6 M BELOW SURFACE FEBRUARY 2-15, 1973

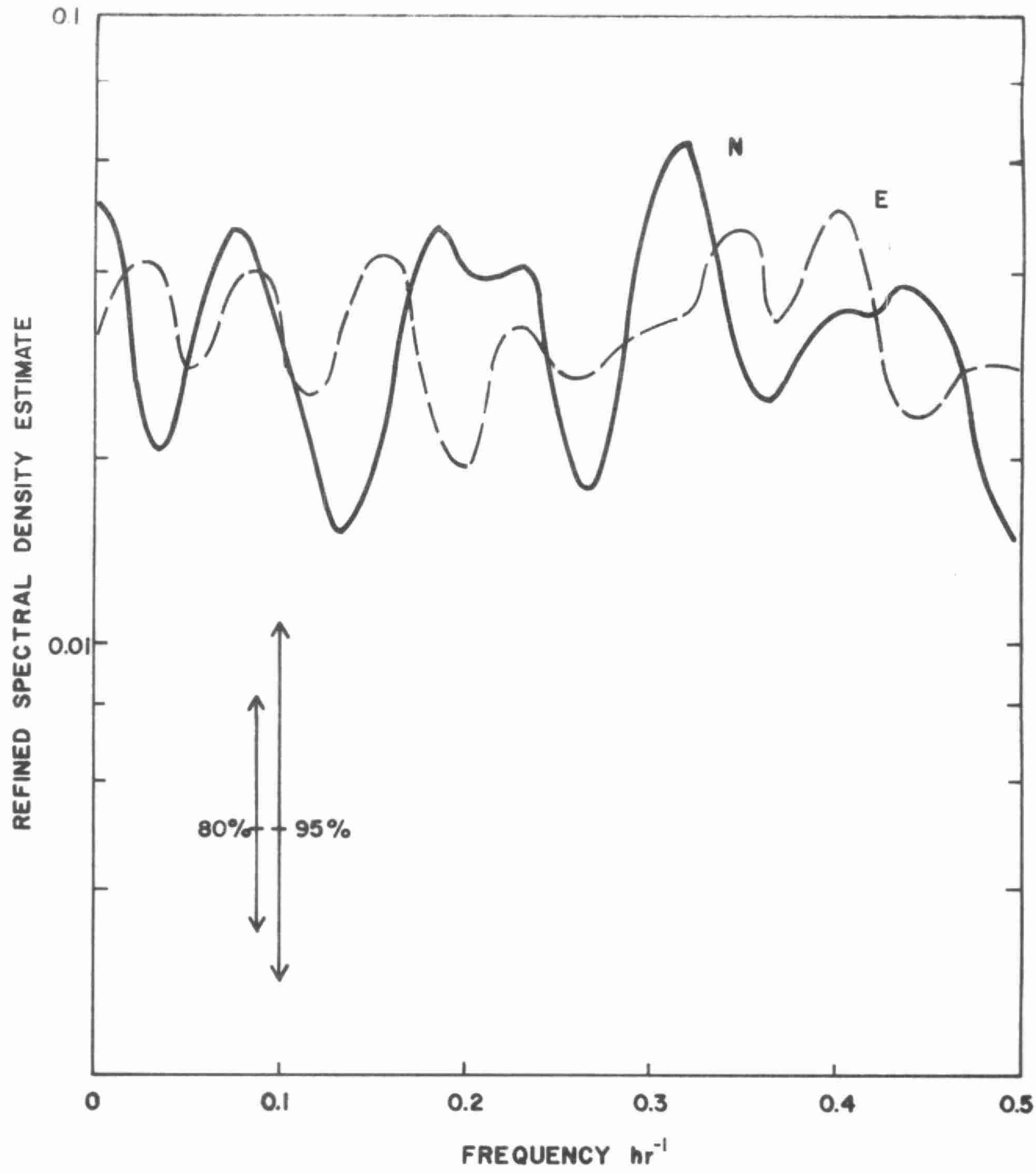

FIG. 4 AUTOSPECTRA FOR CURRENTS, HAMILTON SHIP CANAL SEPTEMBER 12-24, 1972 UPPER LOCATION, 6.7 M. FROM BOTTOM (ROTATED; NORTH IS ALONG THE CHANNEL)

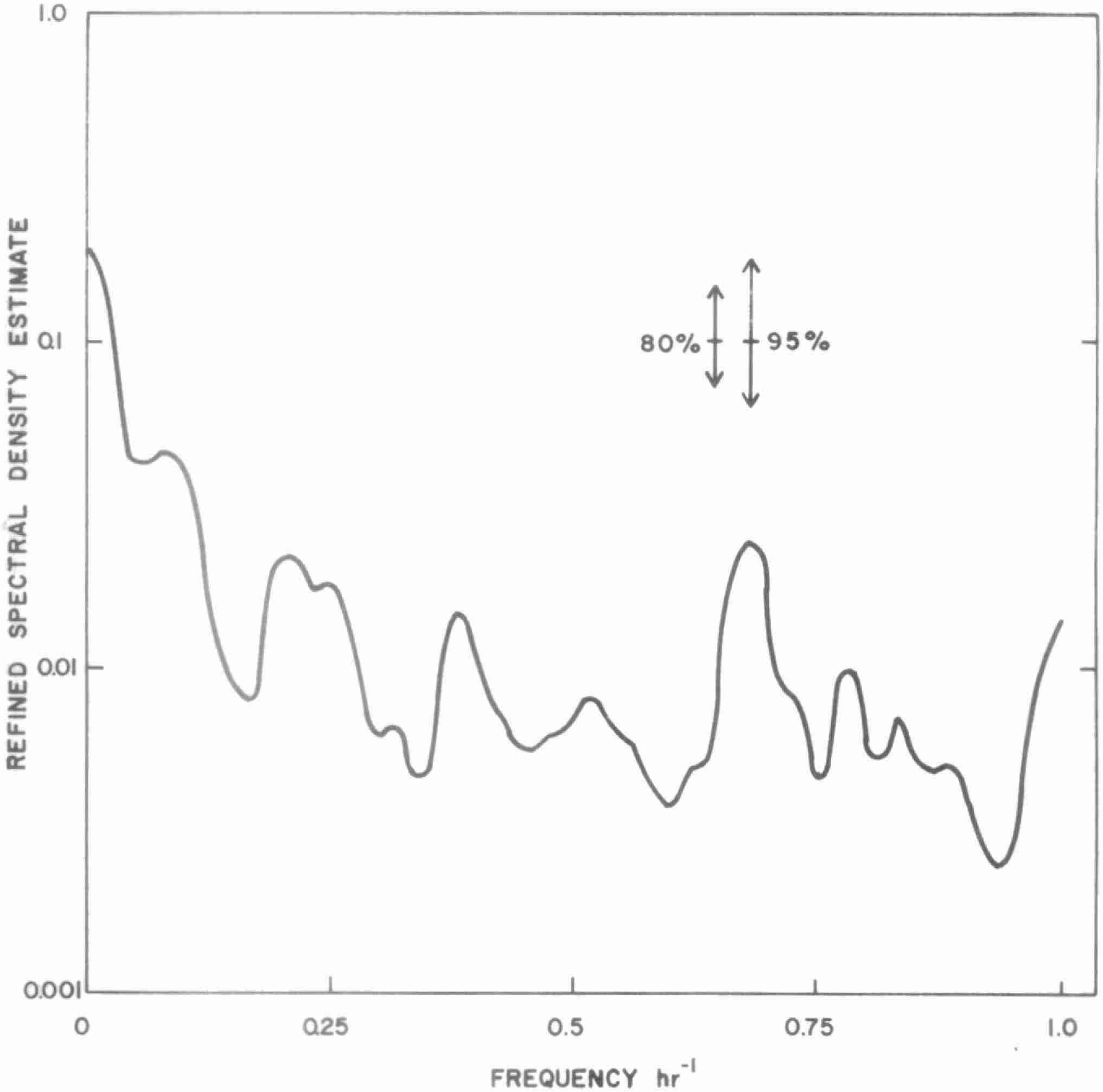

FIG. 5 AUTOSPECTRA FOR NORTH CURRENTS DECEMBER 1972 HAMILTON HARBOUR, LOCATION 114 16 M FROM BOTTOM

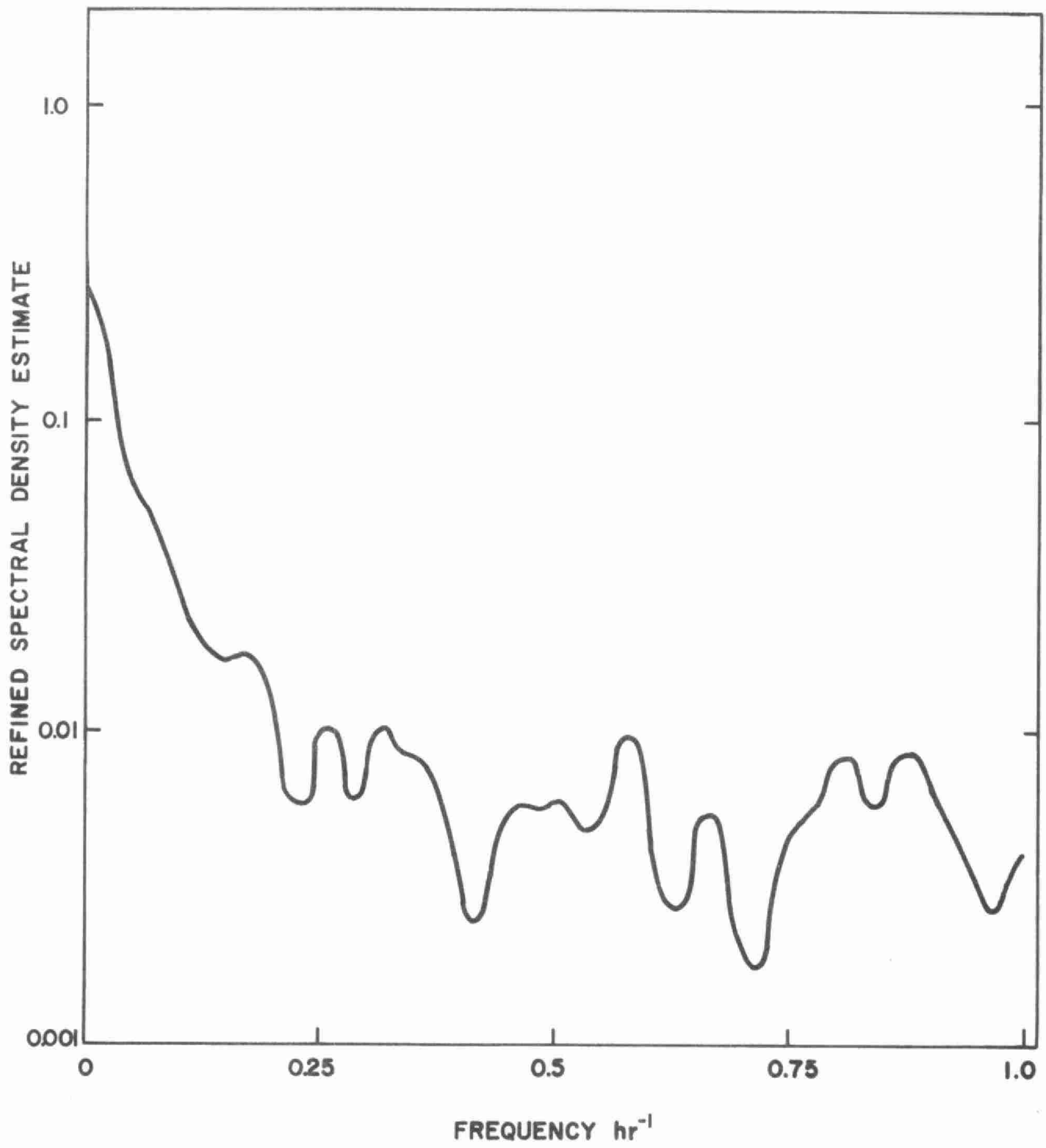

FIG. 6 AUTOSPECTRA FOR EAST CURRENTS DECEMBER 1972
HAMILTON HARBOUR, LOCATION 114 16M FROM BOTTOM

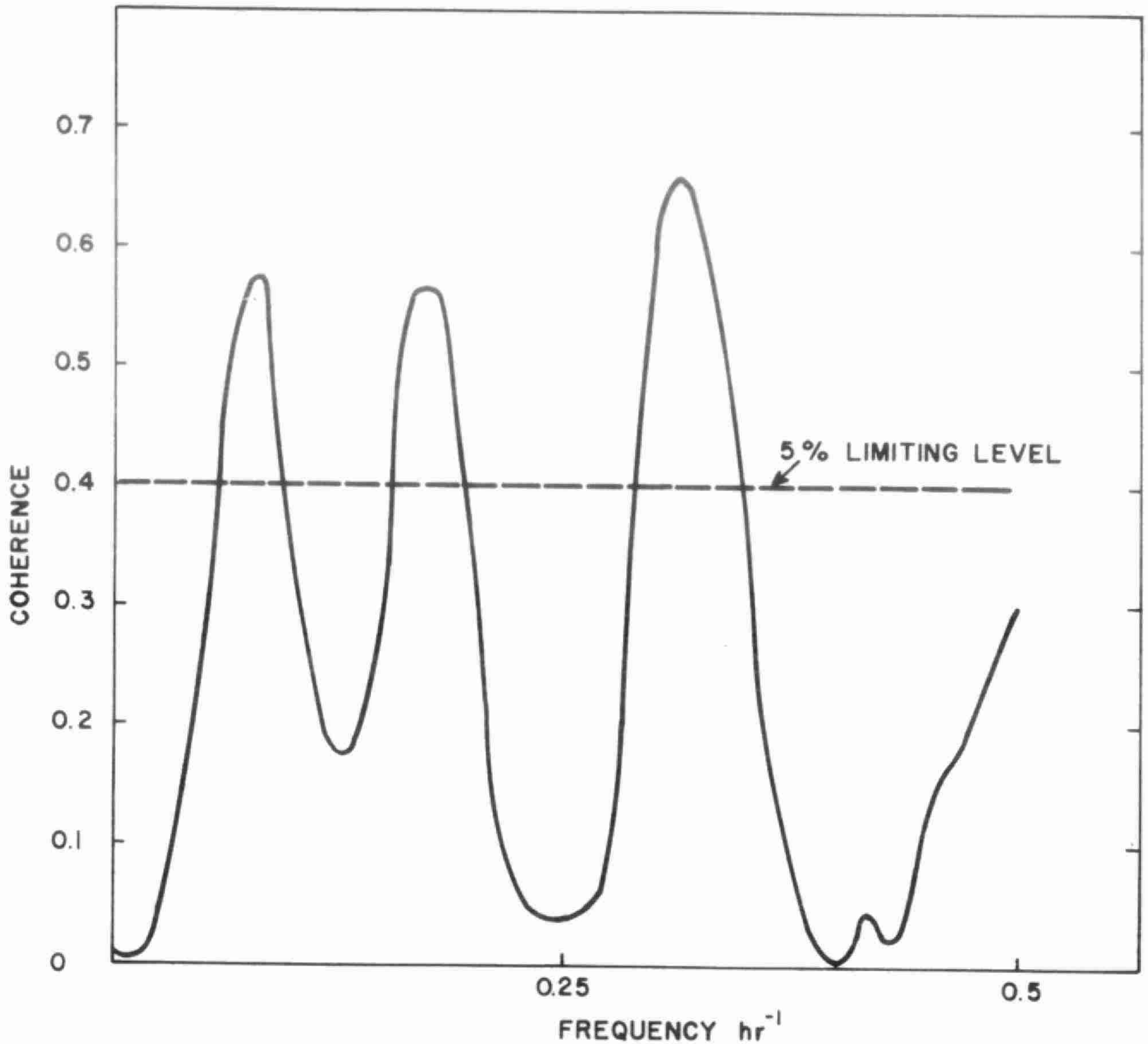

FIG. 7 COHERENCE SPECTRA OF CONDUCTIVITY AND CURRENTS ALONG CHANNEL, SEPTEMBER 12-24, 1972, UPPER LEVEL

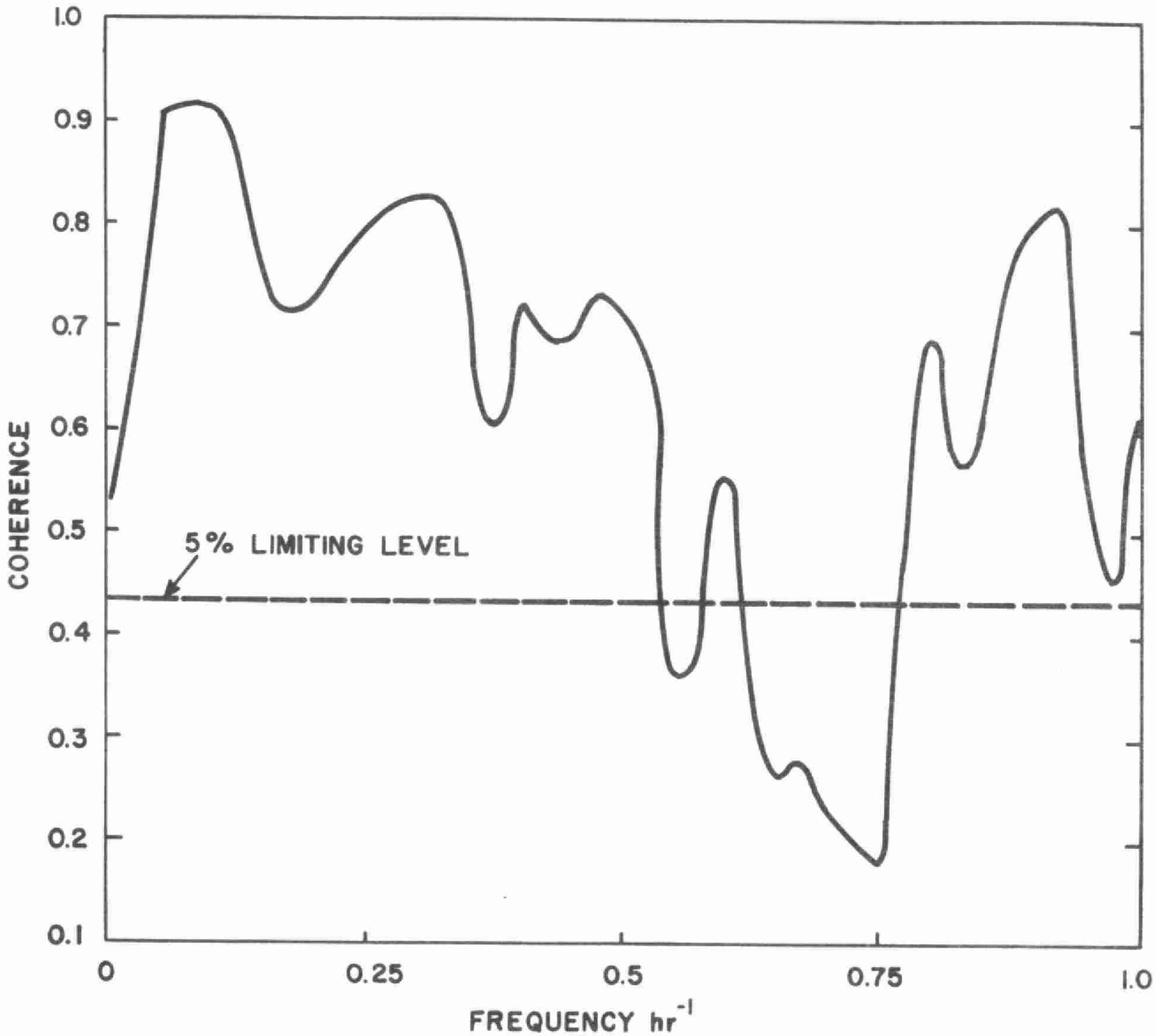

FIG. 8 COHERENCE SPECTRA OF CONDUCTIVITY BETWEEN UPPER AND LOWER LEVELS, BURLINGTON SHIP CANAL, SEPTEMBER 29 - OCTOBER 6, 1973

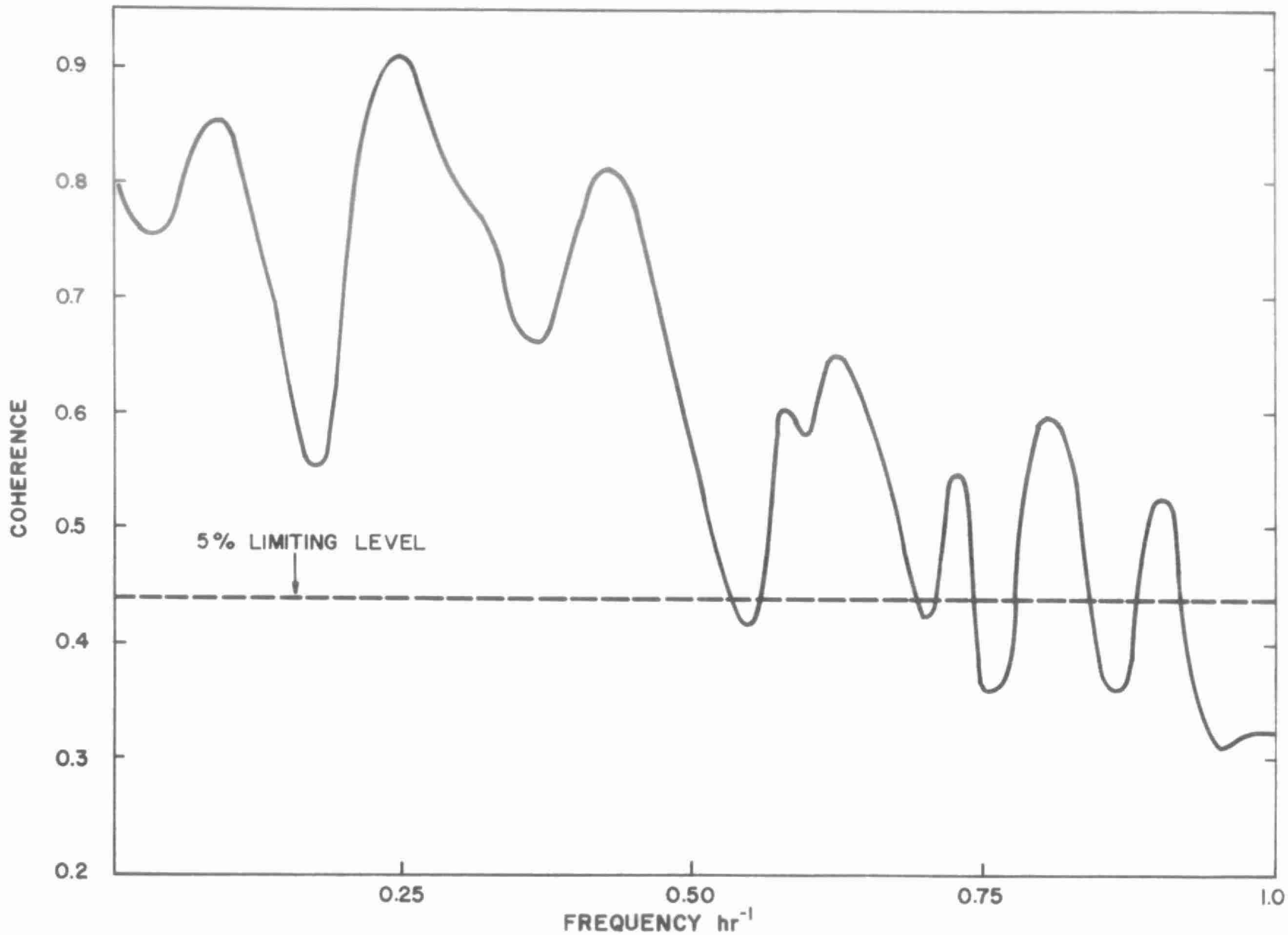

FIG. 9 COHERENCE SPECTRA OF DISSOLVED OXYGEN (mg/L) BETWEEN UPPER AND LOWER LEVELS BURLINGTON SHIP CANAL, SEPTEMBER 29-OCTOBER 6 1973

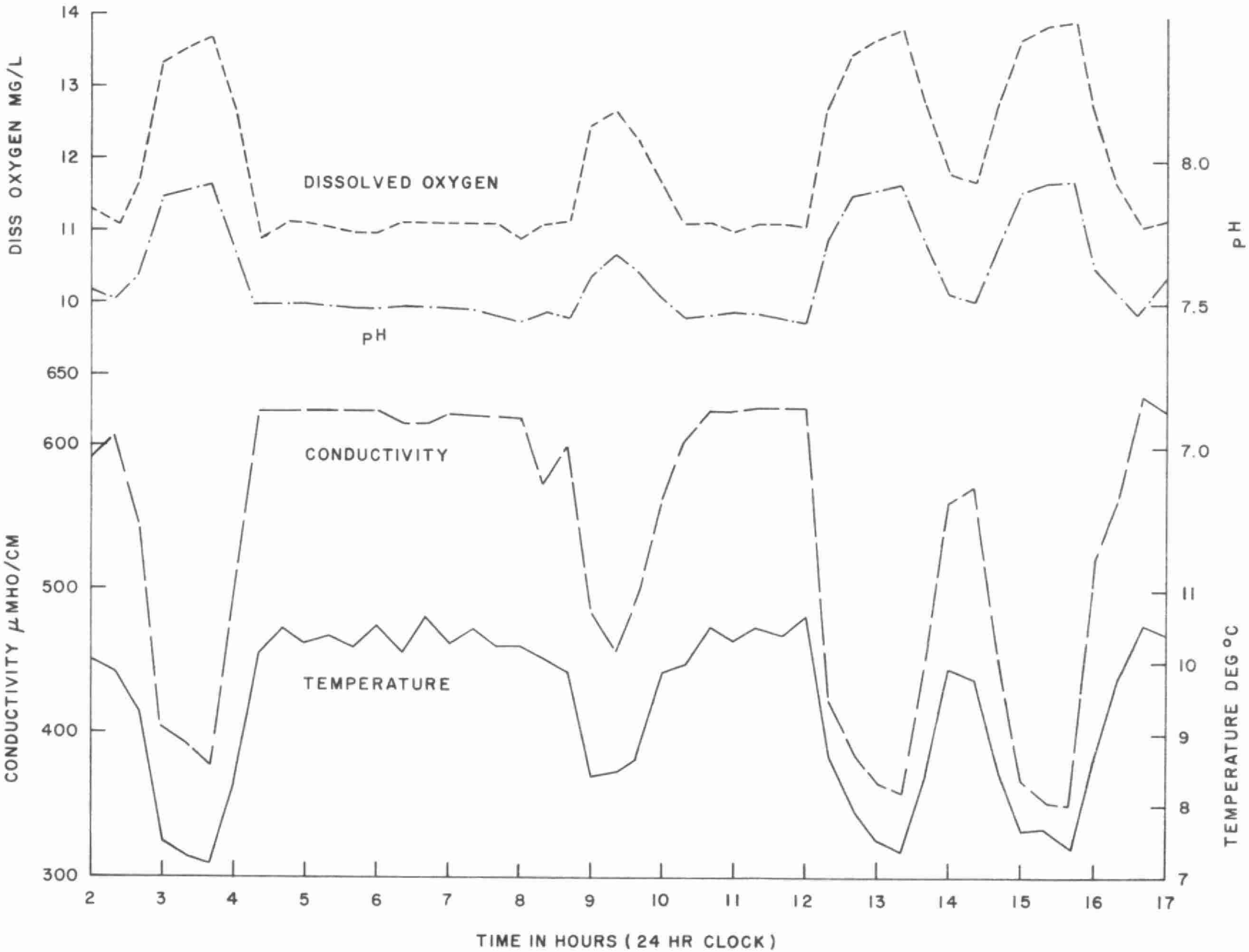

FIG. 10 WATER CHEMISTRY METER IN SHIP CANAL MAY 1, 1973

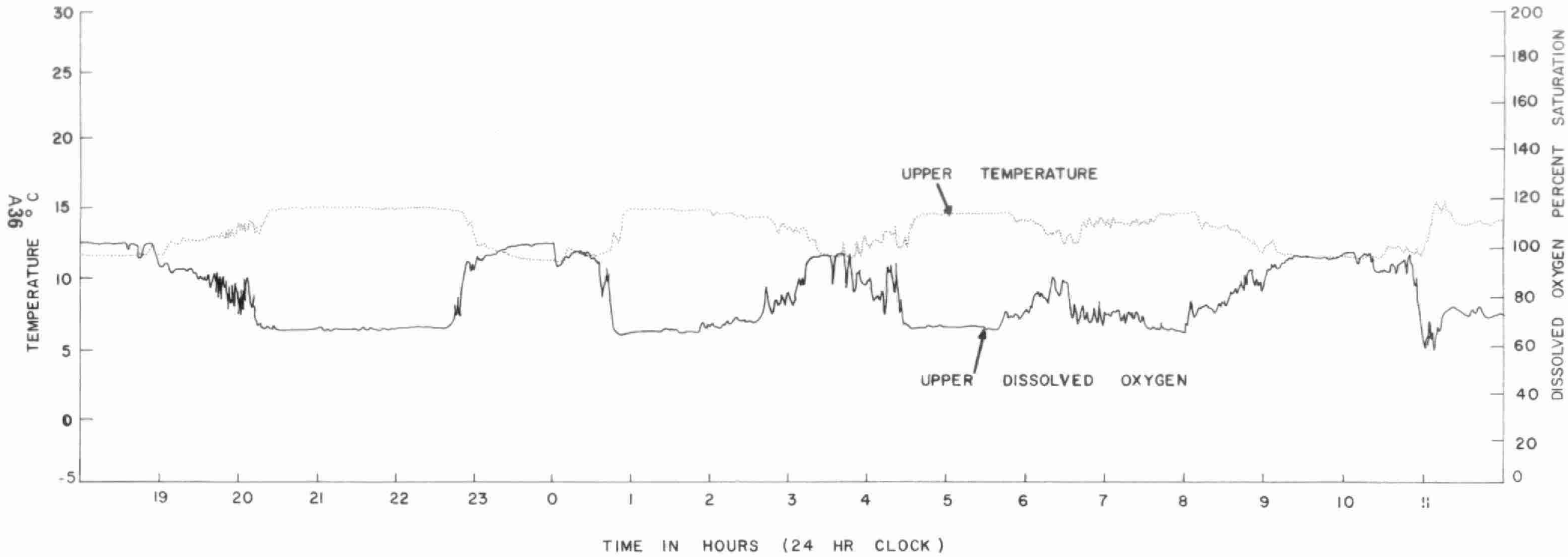

FIG. 11 RECORDING WATER CHEMISTRY METER IN SHIP'S CANAL, 20 - 21 SEPT, 1973.

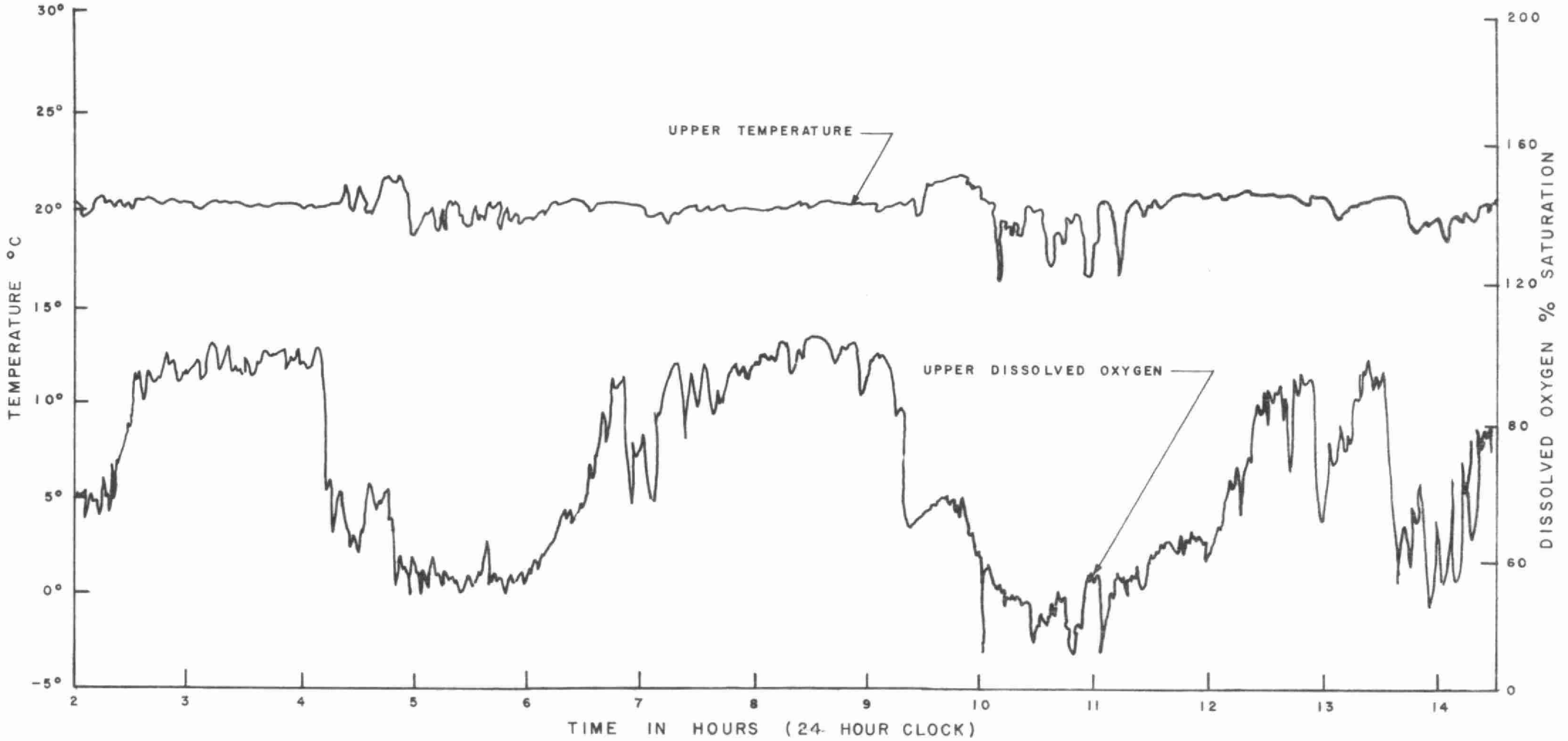

FIGURE 12 : RECORDING CHEMISTRY METER IN SHIP'S CANAL AUGUST 19 1973

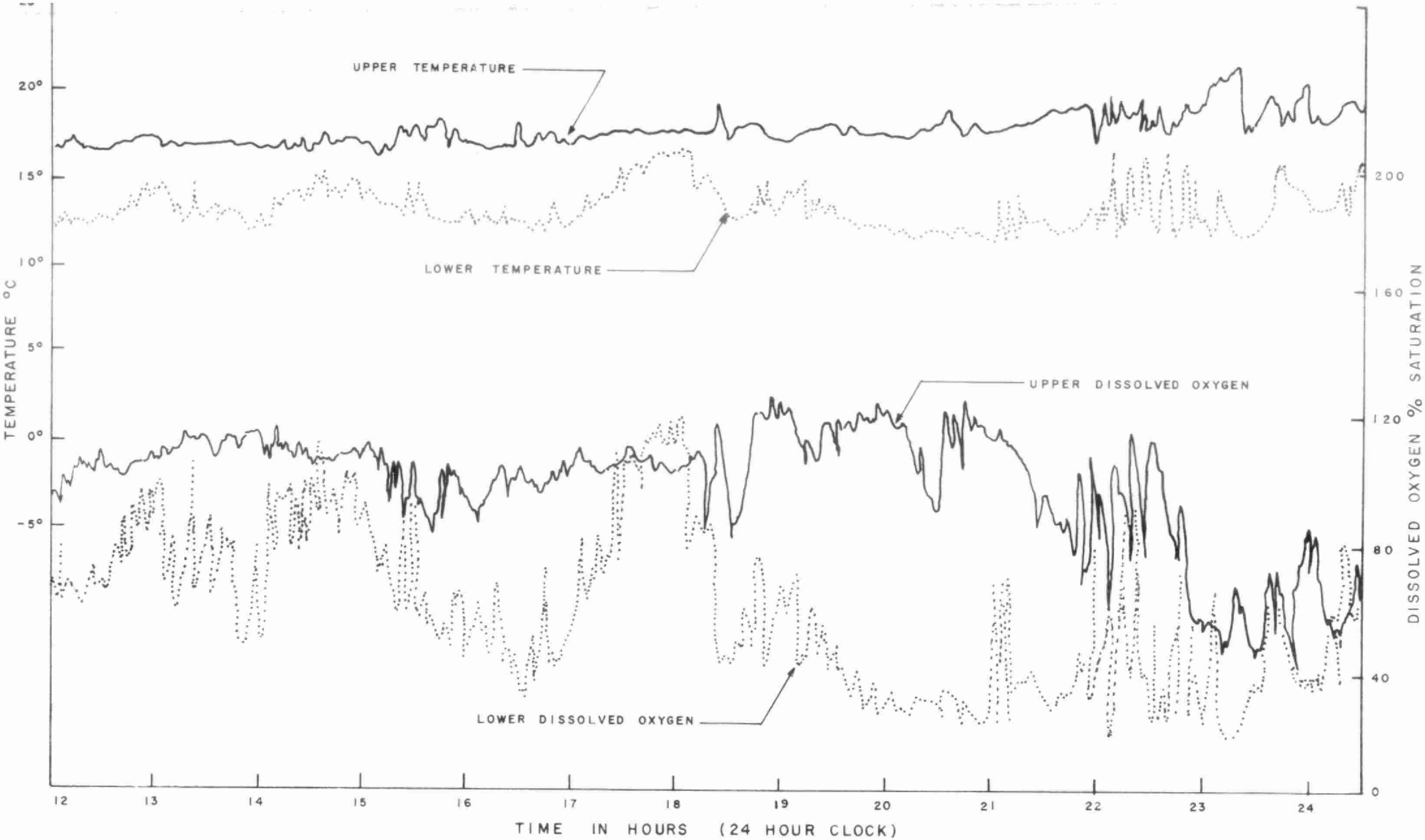

FIGURE 13 : RECORDING CHEMISTRY METER IN SHIP'S CANAL AUGUST 17 1973

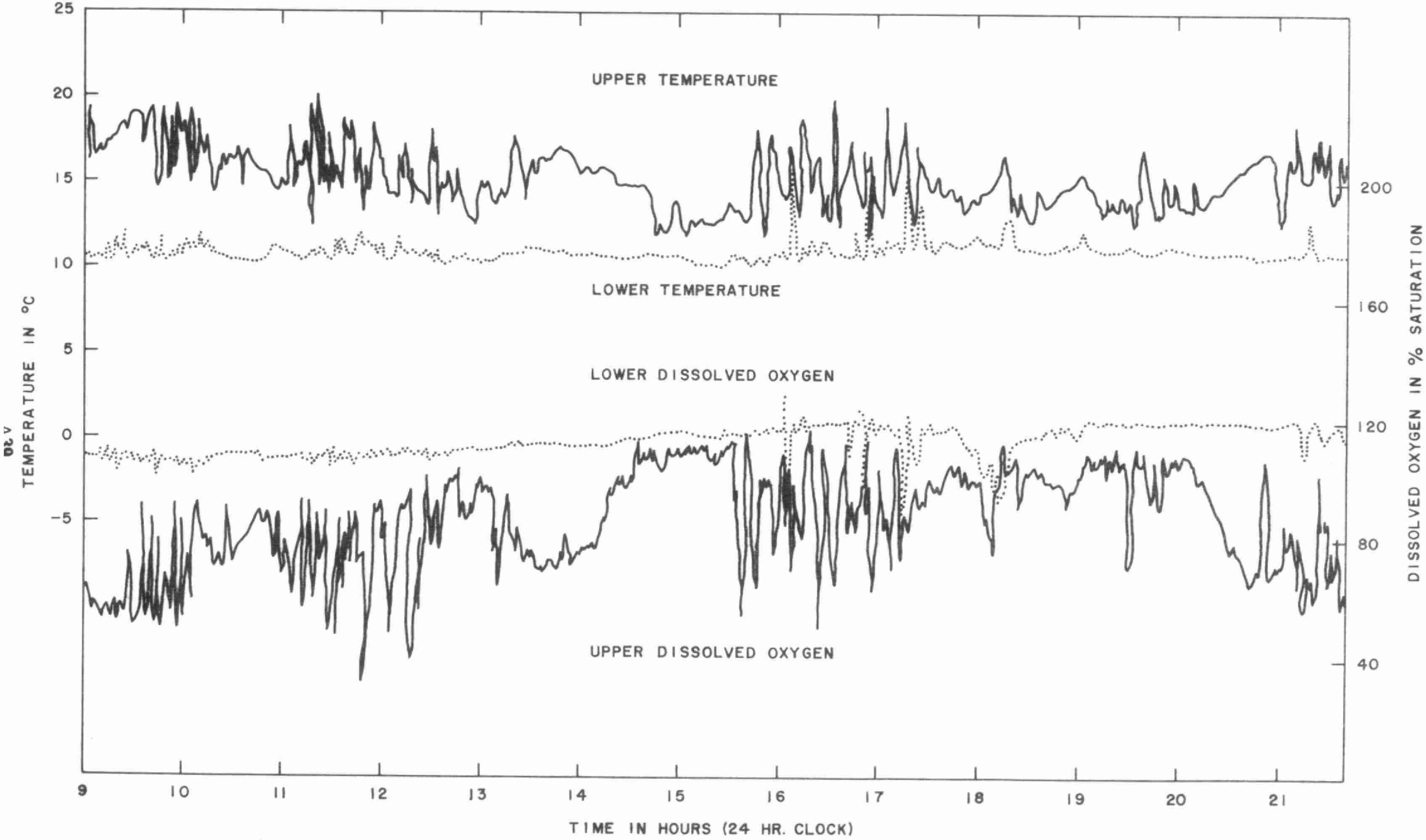

FIG. 14 RECORDING CHEMISTRY METERS IN SHIP'S CANAL AUGUST 16, 1973

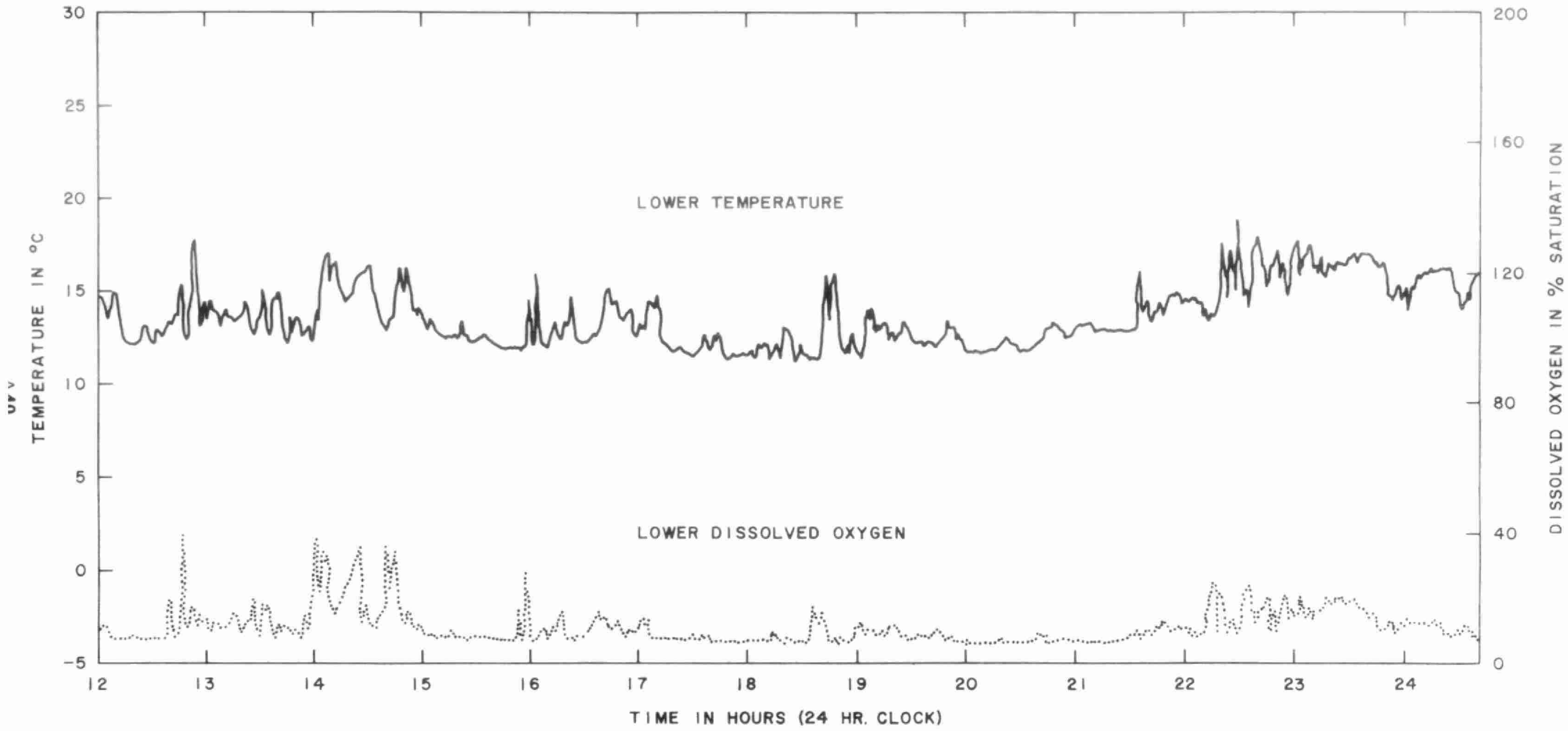

FIG. 15 RECORDING CHEMISTRY METER IN SHIP'S CANAL AUGUST 20, 1973

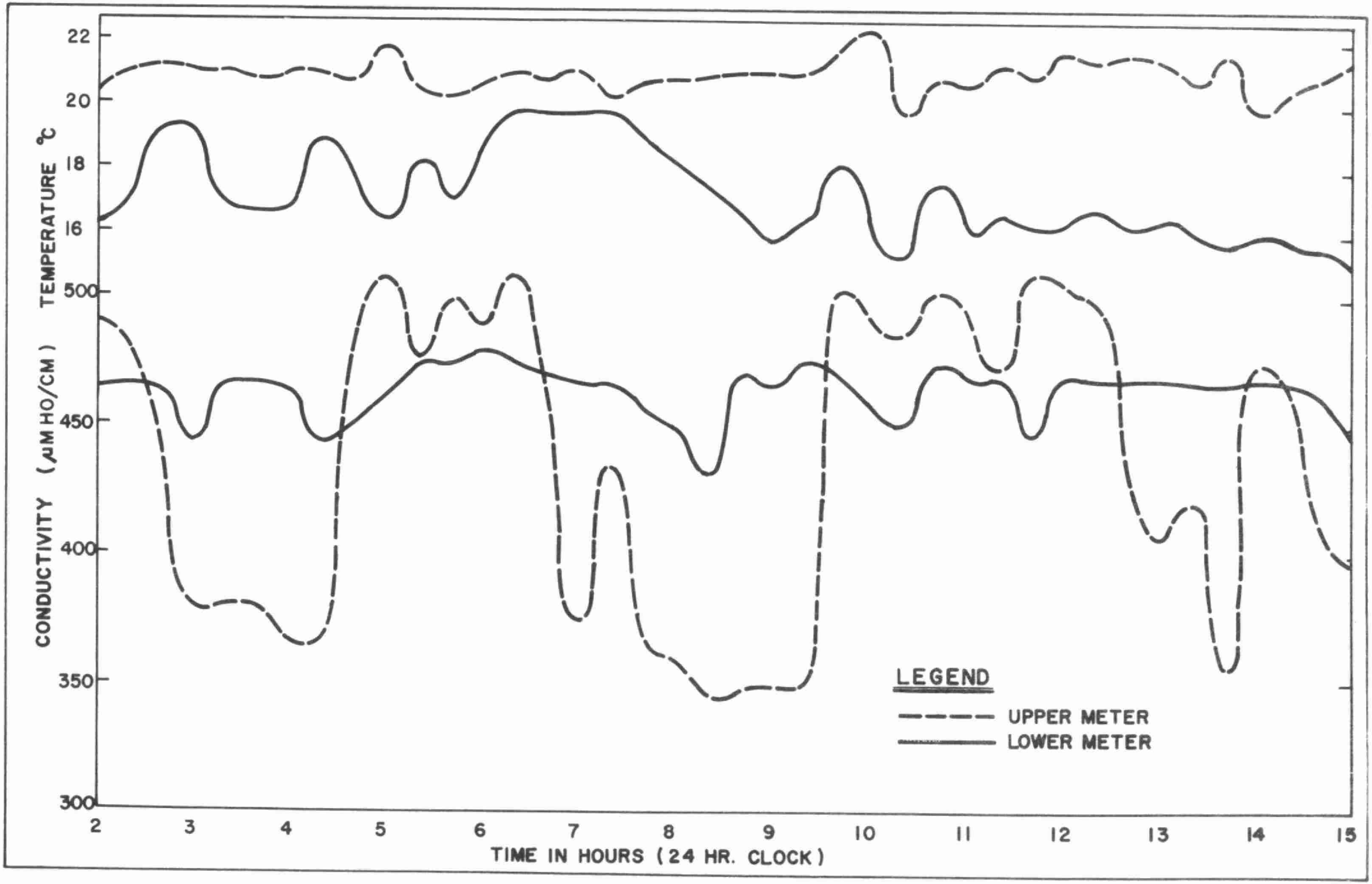

FIG. 16 RECORDING WATER CHEMISTRY METER BURLINGTON SHIP CANAL AUGUST 19, 1973

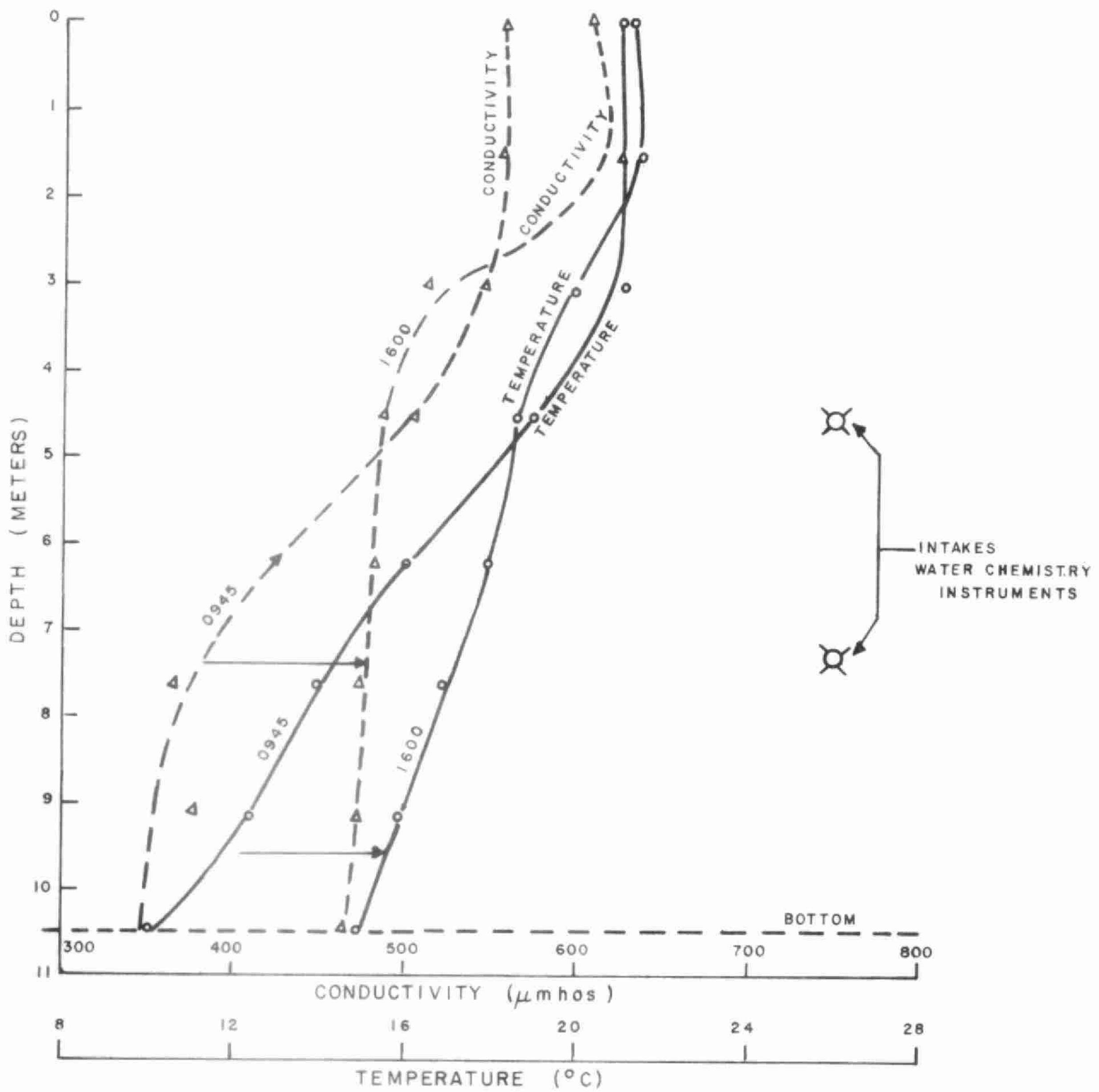

FIGURE 17 : SHIP'S CANAL DEPTH PROFILE
0945 TO 1600 JULY 11 1973

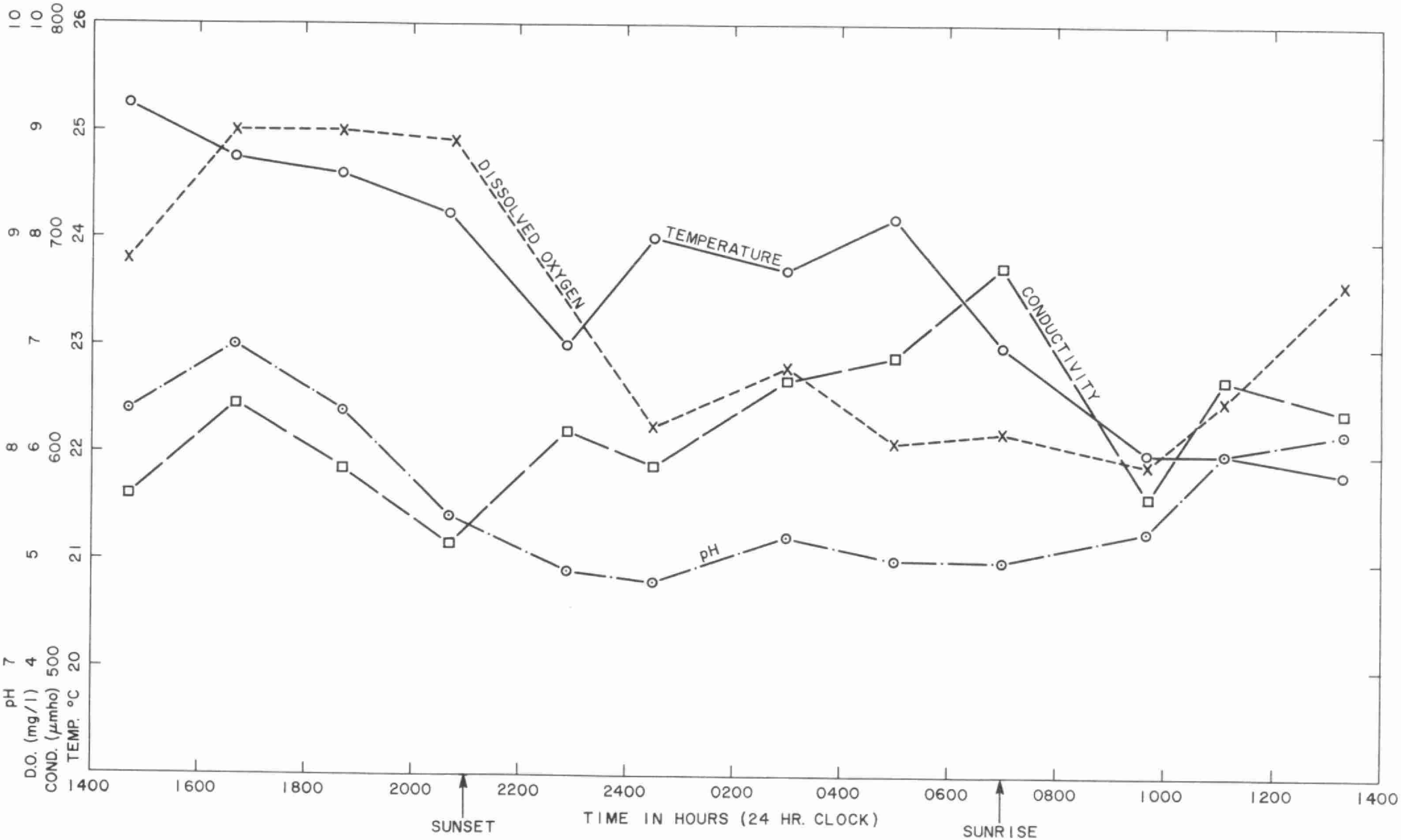

FIG. 18 24 HOUR WATER CHEMISTRY SURVEY JULY 10-11, 1973

HAMILTON HARBOUR STUDY

section B

nutrient trend analysis

HAMILTON HARBOUR STUDY

SECTION B

NUTRIENT TREND ANALYSIS

SUMMARY

TRENDS IN NITROGEN, PHOSPHORUS AND CHLOROPHYLL A CONCENTRATIONS IN HAMILTON HARBOUR SINCE 1966 HAVE BEEN STUDIED. PRIOR TO 1971, THERE WERE NO SIGNIFICANT TRENDS IN INORGANIC NITROGEN (AMMONIA PLUS NITRATE), PHOSPHORUS OR CHLOROPHYLL A. FROM 1971 TO 1972, REDUCED INDUSTRIAL AMMONIA DISCHARGES RESULTED IN A SIGNIFICANT DECREASE IN THIS PARAMETER.

SECCHI DISC, TOTAL PHOSPHORUS AND CHLOROPHYLL A DATA INDICATE THAT THE HARBOUR IS EUTROPHIC. ALTHOUGH THERE IS SOME EVIDENCE FOR LIMITATION OF ALGAL GROWTH BY PHOSPHORUS AND TURBIDITY, LIMITED CONCENTRATIONS RANGES OF THESE PARAMETERS PRECLUDE DEFINITE CONCLUSIONS. THE FACT THAT ANNUAL NITROGEN AND PHOSPHORUS LOADINGS ARE 5 AND 30 TIMES THE TOTAL STOCK OF THESE ELEMENTS IN THE WATER, RESPECTIVELY, INDICATES THE IMPORTANCE OF BIOLOGICAL AND CHEMICAL REMOVAL IN MAINTAINING THEIR PRESENT CONCENTRATIONS.

NUTRIENT REMOVAL COMBINED WITH IMPROVEMENT IN DISSOLVED OXYGEN LEVELS BY REDUCTION OF CHEMICAL OXYGEN DEMAND LOADINGS, ARTIFICIAL DESTRATIFICATION AND POSSIBLY SEDIMENT REMOVAL ARE THE BEST POSSIBILITIES FOR FUTURE IMPROVEMENT IN THE TROPHIC STATE OF HAMILTON HARBOUR.

HAMILTON HARBOUR STUDY

NUTRIENT TREND ANALYSIS

Introduction

An important aspect of the limnology of Hamilton Harbour is the concentration of nutrients available to biological growth, their sources, sinks, and the effect of the biological growth on the use of Hamilton Harbour and Lake Ontario water, both by industries and for municipal water supply. Wastes discharged to Hamilton Harbour are recognized as the chief source of water quality degradation in the western end of Lake Ontario. The presence of ammonia in the western end of Lake Ontario, and particularly in Hamilton and Burlington water works intakes, is well documented (Matheson, 1962, 1963; Matheson and Anderson, 1965).

Prior to 1964, untreated sewage from Hamilton was discharged into the Ottawa Street slip. Ammonia concentrations in the bay increased from an average of 1.0 mg/l N in 1948-9 to 4 mg/l N in 1960-1, and nitrate concentrations increased from 0.6 mg/l N in 1949-50 to 1.2 mg/l N in 1961 (Matheson, 1963). As part of a biological survey conducted by OWRC in August and September 1964 (OWRC, 1966), average total phosphorus was measured as 0.09 and 0.12 mg/l P and total kjeldahl nitrogen was 4.3 and 3.3 mg/l N in surface and deep water, respectively. Since 1964, a primary sewage treatment plant has discharged sewage into the mouth of Red Hill Creek entering the extreme southeast corner of the bay. However, in older parts of Hamilton, combined storm and sanitary sewers exist, which under periods of heavy precipitation discharge significant amounts of untreated sewage to the harbour. The effect of these sewer outfalls has been discussed in detail (OWRC, 1967). The sewer overflow loadings were generally at least an order of magnitude less than the principal industrial loadings.

The Hamilton municipal laboratories have measured ammonia, nitrate, total and soluble phosphorus and chlorophyll a at weekly to biweekly intervals in the growing seasons of 1966 to 1971 (Hamilton Department of Municipal Laboratories, 1966-1971). Surface samples were obtained at a network similar to the 8-station MOE grid, with the exception of station 252. Some figures for total chlorophyll have also been reported for 1963 to 1965 (Matheson and Anderson, 1966).

In the intensive survey conducted by MOE in 1972, nitrogen (ammonia, total kjeldahl, nitrite and nitrate), and phosphorus (total and soluble) data were obtained at the surface, 1.5 m intervals to 6 m, and at 3 m intervals to the bottom at eight stations on two spring dates and approximately weekly from mid-July to mid-November. On the same dates, depth composite chlorophyll a samples were also obtained. Data were also obtained from 17 stations on 4 dates from August to November. Figure 1 indicates the location of the sampling stations used.

Comparisons of data collected by different laboratories and analyzed by different methods can obviously be misleading, particularly the older results which were not restricted in their methods. When possible, results from the same laboratory are compared. If inter-laboratory comparisons are necessary, a comparative factor is evolved or the comparisons are qualitatively treated.

Surveys of the industrial discharges to Hamilton Harbour were performed by Industrial Wastes Branch four times between April, 1972 and January, 1973. Approximately monthly determinations of nutrients (N and P) in the treated effluents from Hamilton and Burlington Skyway WPCP's were also made.

In this bulletin, trends in nutrient (N and P) and chlorophyll a concentrations since 1966 are studied. Annual mean concentrations of each nutrient and chlorophyll a were calculated for each station using all samples taken between June and October. Monthly means of all samples taken in the harbour were also calculated. The June to October period was selected in order to include as much data as possible, without introducing a serious bias from the seasonal variation observed with these parameters. Results of these calculations are presented in Tables 1 to 5. Present nutrient concentrations and their spatial and temporal variations are presented and compared with industrial and municipal loading data. Results show that the harbour is acting as a sink for considerable amounts of nitrogen and phosphorus, with both chemical and biological mechanisms being important in their removal.

Nitrogen

The highest annual averages for ammonia (Table 1) were recorded in 1970 (6.9 mg/l N) and 1971 (5.9 mg/l N). In 1972, a large drop in ammonia concentration was evident during the entire growing season, the annual mean being 1.7 mg/l N. This is at least partly a result of decreases in industrial discharge of ammonia at Stelco and Dofasco. Ammonia is a by-product of the coke making operations and both companies have expanded coking facilities in recent years, Dofasco in 1967 and 1971 and Stelco in 1968. Dofasco installed equipment for the removal of ammonia in late 1971 and further improvements are presently occurring. These improvements are reflected in a decrease in mean daily discharges from 2200 kg/day in the first six months of 1971 to 1000 kg/day in the last six months of 1972 (data calculated from chemical analyses performed by Ontario Research foundation with occasional batch discharges neglected). Stelco has negotiated for the acceptance of ammonia bearing wastes into the City of Hamilton sanitary sewerage system where the ammonia will be treated at the municipal sewage treatment plant. The diversion occurred early in 1974.

These continuing decreases in ammonia discharge, including elimination of batch discharges, should result in a further decrease in the mean

harbour ammonia concentration within the next few years. It is likely that values within the MOE public surface water criterion of 0.5 mg/l N may be reached.

The maximum annual average for nitrate (Table 2) occurred in 1967 (2.7 mg/l N). That this is the result of increased bacterial nitrification is indicated by the constant value of total inorganic nitrogen (5.5 mg/l N, = NH_3-N + NO_3-N, assuming nitrite to be unimportant in comparison) observed between 1966 and 1969. The monthly average data (Tables 1-2) indicate that nitrification tends to be predominant early in the summer, the maximum nitrate content being reached in July or August. After this, nitrate reduction is important, although the ammonia concentration also drops as a result of biochemical utilization.

Phosphorus

Although the total annual phosphorus concentrations (Table 3) tend to increase gradually from 1968 to 1972, the trend is not clearcut, as individual station variations are quite random. Data for station 20, in particular, are quite variable. The mean figures for this station in 1970 and 1971 were influenced by several high readings. As Hamilton has an overflow system, a possible correlation between rainfall and phosphorus might be expected. Accordingly, data at station 20 for 1970 to 1972 were compared with rainfall data. (Department of Transport, 1970, 1971, 1972). The raw data are given in Table 6. In order to minimize random effects after low rainfalls, results for days with less than 1 cm rainfall were averaged. The results, plotted in Figure 6, indicate no statistically significant relationship exists between large rainfalls and high concentrations of total phosphorus. As total phosphorus is a sensitive water quality parameter for the urban areas of the lakeshore (Palmer and Sato, 1968; Brydges, 1969), it is reasonable to assume that storm water overflows are not influencing the water quality at the sampling locations used. Although a better correlation might be obtained if the increase in total phosphorus concentration after rainfall were correlated with rainfall (Brydges, 1969), this was not possible in Hamilton Harbour due to the lack of daily sampling.

At all stations except 20, the total phosphorus concentration appeared to increase from 1971 (Hamilton laboratory study) to 1972 (MOE study). This resulted from the different analytical procedures for total phosphorus used by the two laboratories. Samples analyzed by MOE were boiled to fumes with sulfuric acid and potassium persulfate, while in the Hamilton municipal lab, samples were boiled for only 30 minutes. As organic compounds containing C-P bonds are hydrolyzed by the former, but not the latter procedure, the MOE results are higher by a factor of 1.5 $\pm$ 0.5 (figure obtained from samples collected in the spring of 1972 and analyzed by both laboratories).

As soluble phosphorus is difficult to measure accurately (Brydges, 1971a) it is felt that no significant trends exist in this parameter.

Chlorophyll 'a'

The mean chlorophyll a concentration in Hamilton Harbour in the period 1966-72 was 23 ug/l. No significant trends from one year to the next are indicated in Table 5. In particular, the apparent decrease from 1971 to 1972 is an artifact of the lack of data in October 1971 (low chlorophyll a expected on the basis of historical seasonal trends) and June 1972 (high chlorophyll a expected).

All data obtained place Hamilton Harbour well within the range of values typical for eutrophic lakes (OWRC, 1971; Michalski, 1973). The average 1972 secchi disc depth of 0.75 m is in agreement with the approximately hyperbolic relationship between these parameters described in the above references.

As biological growth is related to nutrient availability, the relationships between chlorophyll a and nutrient concentrations were examined by linear regression. Christie (1973) found a highly significant linear relationship between chlorophyll a and biomass (ASU or cm^3m^{-3}) for the Bay of Quinte. Station means for chlorophyll a and total phosphorus, along with ammonia, turbidity and secchi disc are presented in Table 7 for all data gathered between July 21 and October 5, 1972. The relationship between chlorophyll a and total phosphorus is indicated in Figure 2. The equation of the regression line is:

Chlor a (ug/l) = 17.9 + 54 tot P (mg/l)

$r = 0.588$, $F = 7.94$ (significant at $\alpha = 0.05$)

Although this line statistically fits the points, it is environmentally impossible because one cannot have a significant chlorophyll a concentration at zero total phosphorus. The high total phosphorus concentrations at station 20 and 252 are in the immediate vicinity of the municipal WPCP outfalls. It has generally been observed that algae levels near such outfalls are lower than those predicted for the observed total phosphorus data; although bacteria may play a role, the exact cause of this deviation is uncertain. If data from these stations are omitted, a line approximating Brydges (1971) Lake Erie data is obtained. The limited range of chlorophyll a (17 to 28 ug/l) and total phosphorus (40 to 200 ug/l) values in Hamilton Harbour when compared to the Lake Erie data limits the significance of statistical linear fitting in Hamilton Harbour, and it is not possible to show that chlorophyll a levels are related to total phosphorus concentrations in a similar manner to Lake Erie. The high concentrations of total phosphorus suggest that other factors may be limiting like nitrogen, turbidity, or phytoplankton density.

No statistically significant linear relationship was found between chlorophyll a and any nitrogen parameter.

If the data in Table 7 are divided at a chlorophyll a value of 22 ug/l, the stations above this value are located along the north shore of the harbour. An exception is station 20, where high total phosphorus and ammonia from the Hamilton WPCP permit higher chlorophyll a values. This spatial variation is shown in Figure 7. Statistical 't' tests on the data support the representation in Figure 7.

As the availability of light may have a limiting role in phytoplankton production in waters of high turbidity, chlorophyll a was investigated as a function of turbidity and secchi disc. Increased phytoplankton densities affect secchi disc to a greater extent than turbidity. Data are given in Table 7. However, as the range of values of turbidity and secchi disc was insufficient to indicate any relationships, no general conclusions could be drawn. A possible exception was at station 256 (off Ottawa Street slip), where the chlorophyll a values are the lowest while the total phosphorus (Table 3) concentrations and turbidity (Table 7) levels are the second highest in the harbour. It appears that turbidity is limiting at station 256, at least at depths below 1.5 m (chlorophyll a samples were depth composite samples from 1.5 m from the surface to near the bottom). On the other hand, it is possible that chlorophyll concentrations may have been much higher next to the surface, where light is plentiful. Station 256 has historically had the highest turbidity values (Table 8).

Higher chlorophyll a might have been expected at station 265, on the basis that clearer water near the north shore permits more efficient nutrient utilization. As the nutrient levels at this station are comparable to the rest of the bay, it is suggested that currents in this area (see predicted currents, Section E) may cause an increased turbidity level due to suspension of bottom material, resulting in some light limitation to algal growth at this location.

Nutrient Loading Data

Mean industrial and municipal loadings for ammonia, nitrate and total phosphorus in 1972, from data gathered by the Industrial Wastes and Project Operations branches, are presented in Table 9. The industrial data are means of four surveys conducted between April 1972 and January 1973. In general, composite samples were taken over a six-hour period. The municipal data are means of monthly composite samples.

It is useful to use this data in numerical modelling of nutrient concentrations in Hamilton Harbour, as the model (Section E) includes kinetic terms for reaction of non-conservative parameters, such as nutrients or BOD. It would also be helpful if these figures could be related to spatial and temporal variations in harbour nutrient concentrations, as observed in the weekly surveys. However, the loadings are highly variable, as indicated by the indices of variation, and such computations are not practical at this time.

The total stock of ammonia, nitrate and total phosphorus in Hamilton Harbour was calculated for August 6-7, 1972, by integrating the nutrient-depth profiles at each sampling station as done for DO in Section D. The results obtained are: ammonia, 3.24×10^5 Kg as N; nitrate, 4.19×10^5 Kg as N; and total phosphorus, 1.57×10^4 Kg as P. By comparison, the annual loadings of inorganic nitrogen ($NH_3 + NO_3$) and total phosphorus are 4.0×10^6 Kg as N and 4.7×10^5 Kg as P (calculated from Table 9). The added phosphorus is removed by biological assimilation and sedimentation, as well as chemical precipitation as $FePO_4$ (Section C). Pathways of nitrogen removal include biological assimilation followed by sedimentation of organic nitrogen, as well as nitrification of ammonia followed by denitrification to gaseous nitrogen (AWWA, 1964). Adsorption of ammonia by the oxidized microzone of the mud may be important (Hutchinson, 1957, p. 859), though results obtained on different lakes are inconsistent (Hutchinson, 1957, p. 860). Observed seasonal trends for ammonia, nitrate and total kjeldahl nitrogen are given in Table 11 and Figures 3 to 5. The spring decrease in total kjeldahl nitrogen (ammonia plus organic nitrogen), without a corresponding increase in nitrate concentration is evidence for sedimentation of organic nitrogen. That biological utilization of ammonia has occurred is indicated by the observed increase in concentration of organic nitrogen from near zero to about 1 mg/l between March and July, 1972. Much of this organic nitrogen is eventually sedimented as stable refractory compounds of uncertain composition, but believed to be similar to soil compounds (AWWA, 1964), while the remainder is released as ammonia and recycled.

A considerable quantity of the nutrients released by the Hamilton WPCP are probably assimilated in Windermere Basin, southeast of station 20. This is shown by the Hamilton municipal laboratory figures for total phosphorus and chlorophyll a (Hamilton Department of Municipal Laboratories, 1970) for the three industrial shore stations nearest the WPCP outfall. The 1970 total phosphorus average was 1.7 mg/l P and the chlorophyll a average was 200 ug/l. (Effluent total P was 6 mg/l P for 1967-9 and 4.1 mg/l in 1972). Therefore, the true loading of the Hamilton WPCP to the main portion of the harbour is certainly much less than the figures given in Table 9.

As the majority of the nutrients released by the Dundas WPCP are assimilated in Coote's Paradise, and the relative loadings are small, this plant was not considered. The decrease in ammonia concentration in Hamilton Harbour which has occurred despite the magnitude of the loadings indicates the importance of denitrification and sedimentation. Emission of harbour water to Lake Ontario is also important (ammonia results for the west end of Lake Ontario are presented by Matheson, 1963), although the effect of lake-harbour exchange is confined to a relatively small area near the canal (see Section E).

The 1972 annual nutrient loadings per unit area were 190 g/m^2 yr N and 22 g/m^2 yr P. These are approximately 50 and 100 times the dangerous limits advocated by Vollenweider (IJC, 1969, p. 258-9). However, the effect of assimilation in Windermere Basin, combined with chemical sedimentation of P as $FePO_4$ will result in a reduced impact of these nutrients, particularly phosphorus. If the municipal and industrial loadings of total phosphorus are reduced by 95 percent, according to IJC recommendations (IJC, 1969, p. 271-280),

the industrial and municipal loading would be 2.4×10^4 kg/yr, or 1.1 g/m^2 yr P. To this figure, an estimate for total phosphorus yield due to runoff from the watershed should be added. Averaging yields from several partially urbanized agricultural areas (OWRC, 1970, p. 10), runoff might be expected to contribute about 1.5×10^4 Kg/yr, or 0.7 g/m^2 yr P to Hamilton Harbour. Thus the minimum projected loading would be under 2 g/m^2 yr P. However, as the 95 percent reduction in loading is unlikely to be realized in practice, the minimum loading will be greater than 2 g/m^2 yr P, or approximately one order of magnitude above Vollenweider's dangerous limits, however the chemical sedimentation of $FePO_4$ may be sufficient to produce a change in the trophic state of Hamilton Harbour.

As the discharges are in the epilimnion, phosphorus will still be accumulated in the epilimnion. Artificially destratifying the system will effectively distribute epilimnetic accumulations throughout the water column thereby promoting a change in the trophic state. There is of course the possibility of increased phytoplankton density as algae can survive the period of recycling from the photic zone to deeper waters then back to the photic zone. This survival will be a function of the recycling time for the destratification and the chemical properties in the deeper waters and would have to be investigated in the design of the destratification system.

In 1967, an intensive survey of storm sewer outfalls to Hamilton Harbour was performed (OWRC, 1967). Ammonia and total phosphorus loadings from three major outfalls are indicated in Table 10. As these figures are much lower than the variations in industrial data (Table 9), they were not further considered. Since they were obtained during extremely light rainfall conditions, significant loadings may occur during heavy rainfall, when untreated sewage from the combined sewer system existing in parts of the city may be bypassed directly to the bay.

Seasonal Trends in 1972

In order to illustrate seasonal variations of nutrient and chlorophyll concentration, the mean values of all surface samples obtained in 1972 are tabulated for each date in Table 11. Ammonia and nitrate variations are plotted in Figures 3 and 4 (error bars are one standard deviation). Depth-time distributions of ammonia and total phosphorus in July-November 1972 are plotted in Figures 8-11 for stations 258 and 265.

The chemical and biological pathways of ammonia removal, as well as the spring decrease in ammonia (Figure 3), have already been discussed in connection with the industrial loading data. Figures 8 and 9 indicate that a significant drop in ammonia concentration occurred between August 21 and 29, a period of increased wind-induced circulation (see Section D, dissolved oxygen). Sedimentation of organic nitrogen or adsorbed ammonia (aided by more highly oxidizing conditions at the bottom), may have occurred at this time.

In late October, following complete overturn, a large drop in ammonia concentration, accompanied by an increase in nitrate concentration is shown in Figures 3, 4, 8 and 9. Oxidation of ammonia to nitrate may have occurred at this time.

In natural lakes ammonia accumulates in the hypolimnion in late summer due to anaerobic deamination of organic nitrogen and the falling of dead plankton from the epilimnion (Hutchinson, 1957). When the fall overturn occurs, the hypolimnetic ammonia is released to the full water column resulting in a fall maximum in ammonia concentration. In Hamilton Harbour adjacent to the south shore, ammonia concentrations are higher in the epilimnion and no fall maximum occurs. As all the waste discharges are in the epilimnion, it is apparent that the ammonia industrial loadings are of such a magnitude that natural processes are not observed.

The most distinctive feature of the depth-time distributions of total and soluble phosphorus (Figures 10-13) is the presence of isolated pockets of high total phosphorus concentration, most of which is usually soluble. During stratification, phosphorus concentrations are slightly higher in the epilimnion than in the hypolimnion, consistent with the location of most outfalls.

Phosphorus concentrations in Hamilton Harbour are controlled by precipitation of $FePO_4$ by ferric iron (Section C). Accordingly, high soluble phosphorus concentrations would be expected near the bottom under near anoxic conditions which frequently occurred during August and September 1972 (see Section C, iron-phosphorus relationships, and D, dissolved oxygen). Although high iron (presumably Fe^{2+}) concentrations were sometimes reported at the bottom at station 258, they were not accompanied by increased total or soluble phosphorus concentration. As the observed high total phosphorus values are not correlated with unusual values of Fe, DO, hardness or pH, no explanation for these results is forthcoming at this time.

On an overall basis, no significant seasonal trends in phosphorus (total or soluble) were observed in 1972. Standard deviations of the figures stated in Table 11 are 50 percent to over 100 percent of the means.

Conclusions

In the years 1967 to 1971, there were no significant trends in nitrogen, phosphorus or chlorophyll a in Hamilton Harbour. The maximum annual average of nitrate, 2.7 mg/l in 1967, was related to increased bacterial nitrification. From 1971 to 1972, reduced industrial ammonia discharges resulted in a significant decrease in this parameter.

Secchi disc, chlorophyll a and total phosphorus data indicate that the harbour is eutrophic. Although chlorophyll a and total phosphorus concentrations are similar to those in western Lake Erie, it is not possible to show that total phosphorus limits algae growth due to the limited range

of concentrations of these parameters. Near the Ottawa Street slip, turbidity may be limiting algal growth at depths below 1.5 m, but there is no evidence for such a relationship elsewhere in the harbour. The fact that annual nitrogen and phosphorus loadings are 5 and 30 times the total stock of these elements in the water, respectively, indicates the importance of biological and chemical removal of these elements in maintaining their present concentrations.

Although nutrient removal from the industrial or municipal discharges may produce a change in the trophic state, it is possible that adsorbed or precipitated phosphate in the sediments may be released if low dissolved oxygen concentrations occur (see Section C, iron-phosphate relationships). Despite the fact that very low DO levels were observed over extensive areas in 1972 (see Section D, dissolved oxygen), increased total phosphorus concentrations for this reason have not yet been observed. Nevertheless, improvement in DO levels is desirable to prevent future occurrence of this phenomenon. Nutrient removal combined with improvement in DO levels by reduction of COD loadings, artificial destratification (see Section E, numerical model and D, dissolved oxygen) and possibly sediment removal are the best possibilities for future improvement in the trophic state of Hamilton Harbour.

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TABLE 1

AMMONIA SURFACE DATA, 1966-1972

(a) June-October averages for each station

	Station						
	20	256	257	258	262	265	269
1966	7.3	5.5	3.5	3.4	3.7	3.3	4.2
1967	3.1	3.9	2.4	2.4	3.3	2.8	2.2
1968	5.3	5.3	3.7	3.0	4.6	4.1	3.8
1969	4.7	5.1	3.5	3.4	4.7	3.5	3.1
1970	7.8	7.7	7.0	6.3	8.3	5.9	6.9
1971	7.4	5.8	4.9	5.3	8.5	4.8	5.0
1972	2.6	2.0	1.3	1.6	2.8	1.2	1.7

(b) Monthly and annual averages for entire bay

	June	July	Aug.	Sept.	Oct.	Year
1966	6.0	4.2	3.6	3.1	4.7	4.4
1967	3.8	2.3	2.6	2.2	2.4	2.8
1968	6.8	4.7	3.4	3.0	3.1	4.3
1969	4.9	4.0	1.9	3.3	5.5	4.0
1970	8.9	6.8	7.3	6.4	3.5	6.9
1971	9.3	6.1	4.7	3.7	-	5.9
1972	-	2.4	1.9	1.6	1.5	1.9

Note: All figures are in mg/l as N

Analytical Precision ± about 10%.

Standard deviations of above figures (including station and time variations) are generally 30-50% of the means.

TABLE 2

NITRATE SURFACE DATA, 1966-1972

(a) June-October averages for each station

	Station						
	20	256	257	258	262	265	269
1966	0.93	1.25	1.27	1.03	1.01	1.20	1.11
1967	2.48	2.62	2.79	2.89	2.59	2.74	2.78
1968	0.95	1.13	1.38	1.27	1.31	1.30	1.19
1969	1.11	1.28	1.47	1.43	1.45	1.36	1.38
1970	1.36	1.45	1.99	1.85	1.84	1.81	1.73
1971	1.52	1.92	2.15	2.10	2.07	2.08	2.00
1972	1.27	1.64	1.70	1.78	1.71	1.73	1.61

(b) Monthly and annual averages for entire bay

	June	July	Aug.	Sept.	Oct.	Year
1966	-	-	1.10	1.41	0.56	1.11
1967	1.30	3.84	3.95	1.85	1.16	2.7
1968	0.62	1.85	1.61	1.06	0.85	1.22
1969	0.84	1.82	1.69	1.34	0.94	1.35
1970	0.87	2.40	1.90	1.64	1.99	1.75
1971	1.42	2.22	2.18	1.50	-	1.97
1972	-	1.89	1.77	1.42	1.58	1.65

Note: All figures are in mg/l as N

Analytical Precision ± about 10%.

Standard deviations of above figures (including station and date variations) are generally 30-50% of station means and 20-50% of monthly means.

TABLE 3

TOTAL PHOSPHORUS SURFACE DATA, 1967-1972

(a) June-October averages for each station

	Station						
	20	256	257	258	262	265	269
1967	.112	.091	.087	.067	.077	.103	.126
1968	.099	.060	.034	.035	.050	.092	.048
1969	.093	.084	.044	.043	.049	.061	.067
1970	.275*	.074	.036	.044	.054	.046	.065
1971	.279	.055	.033	.031	.037	.037	.040
1972	.172	.086	.072	.068	.065	.068	.078

(b) Monthly and annual averages for entire bay

	June	July	Aug.	Sept.	Oct.	Year
1967	.075	.081	.107	.120	.102	.095
1968	.048	.060	.058	.075	.068	.060
1969	.058	.048	.037	.087	.094	.063
1970	.099*	.091	.065	.078	.059	.078
1971	.091	.055	.072	.098	-	.073
1972	-	.087	.082	.088	.093	.088

Note: All figures are in mg/l as P

* One questionably high value was omitted

Analytical Precision $\pm$ 0.003 mg/l or 10%, whichever is greater. Standard deviations of above figures (including station and date variations) are generally 50-100% of the means.

TABLE 4

SOLUBLE PHOSPHORUS SURFACE DATA, 1967-1972

(a) June-October averages for each station

	Station						
	20	256	257	258	262	265	269
1967	.060	.060	.058	.056	.114	.100	.098
1968	.067	.023	.025	.022	.028	.047	.035
1969	.045	.041	.021	.027	.029	.031	.032
1970	.150*	.007	.016	.020	.013	.013	.013
1971	.101	.009	.004	.007	.004	.007	.012
1972	.057	.020	.017	.015	.016	.015	.020

(b) Monthly and annual averages for entire bay

	June	July	Aug.	Sept.	Oct.	Year
1967	.054	.058	.091	.080	.064	.075
1968	.033	.034	.037	.040	.040	.036
1969	.018	.023	.014	.040	.071	.052
1970	.056*	.036	.033	.013	.007	.029
1971	.039	.016	.026	.052	-	.029
1972	-	.016	.024	.035	.021	.024

Note: All figures are in mg/l as P

* One questionably high value was omitted

Analytical Precision ± 0.003 mg/l or 10%, whichever is greater. Standard deviations of above figures (including station and date variation) are generally 50-150% of the means.

TABLE 5

CHLOROPHYLL a DATA, 1963-1972

(a) June-October averages for each station

	Station						
	20	256	257	258	262	265	269
1963	38	-	-	21	-	-	21
1964	31	-	-	16	-	-	16
1965	18	-	-	16	-	-	17
1966	35	14	24	24	18	25	26
1967	39	17	29	28	23	27	26
1968	18	12	24	22	20	24	21
1969	23	18	27	27	21	27	24
1970	28	14	18	19	16	20	20
1971	28	19	28	26	17	30	25
1972	28	18	22	18	19	19	20

(b) Monthly and annual averages for entire bay

	June	July	Aug.	Sept.	Oct.	Year
1963	18	28	46	28	13	25
1964	29	18	20	22	13	21
1965	12	17	28	18	13	17
1966	30	22	24	19	-	24
1967	21	27	38	26	22	27
1968	36	25	18	15	17	20
1969	37	17	26	26	15	24
1970	34	18	25	12	7	19
1971	41	15	33	10	-	25
1972	-	23	20	21	18	20

Note: All figures are in ug/l

Data for 1963 to 1965 are 0.65 (total chlorophyll), where 0.65 is the ratio chl a tot chl in the Hamilton and Burlington Waterworks for the same time period (Matheson and Anderson, 1966)

TABLE 6

PHOSPHORUS DATA AT STATION 20

AND RAINFALL

Date	Total PO_4 (mg/l P)	Soluble PO_4 (mg/l P)	Rainfall in 3 days ending on sampling date (cm)
1970 June 12	0.897	0.570	0.3
June 17	0.359	0.293	1.4
June 29	2.93*	1.96*	0.1
July 6	0.082	0.000	0.2
July 13	0.111	0.075	0.5
July 21	0.359	0.245	2.4
Aug. 5	0.098	0.065	0
Aug. 17	0.290	0.196	0
Aug. 26	0.277	0.196	0
Sept. 1	0.065	0.016	1.2
Sept.10	0.189	0.108	1.8
Sept.17	0.342	0.016	2.1
Oct. 7	0.228	0.016	0.7
1971 June 11	0.815	0.489	0
June 24	0.114	0.000	0
July 7	0.147	0.049	1.7
July 16	0.147	0.065	0.1
July 21	0.160	0.124	0.03
Aug. 6	0.258	0.189	0
Aug. 11	0.310	0.212	1.3
Aug. 18	0.150	0.075	0
Aug. 26	0.156	0.098	1.1
Sept.30	0.538	0.342	0

Note *: These values omitted from calculations of averages in Tables 3 and 4

TABLE 6 (cont'd)

Date	Total PO_4 (mg/l P)	Soluble PO_4 (mg/l P)	Rainfall in 3 days ending on sampling date (cm)
1972 July 21	0.102	0.024	0
July 25	0.150	0.027	0.3
Aug. 1	0.035	0.020	2.4
Aug. 6	0.075	0.009	1.8
Aug. 14	0.090	0.030	1.7
Aug. 21	0.080	0.014	0
Aug. 29	0.155	0.096	0.5
Sept. 13	0.360	0.233	0.2
Sept. 19	0.160	0.100	0
Sept. 25	0.080	0.035	0.5
Oct. 5	0.320	0.078	0
Oct. 10	0.060	0.008	0.05
Oct. 18	0.105	0.028	0.1
Oct. 24	0.510	0.120	3.9
Oct. 31	0.300	0.037	0.2

TABLE 7

Average for Period July 21-October 5, 1972

Station	Chlorophyll 'a' ug/l	Total P mg/l	Ammonia mg/l N	Turbidity JTU	Secchi Disc m
15	26.2	0.079	1.2	4.0	0.7
20	28.0	0.201	2.3	5.0	0.7
251	20.8	0.063	1.5	4.3	0.5
252	25.5	0.129	1.5	4.4	0.8
253	23.6	0.057	1.2	4.1	0.8
254	20.2	0.046	1.2	5.3	0.7
255	18.0	0.047	1.2	3.7	0.6
256	17.7	0.063	1.5	5.1	0.7
257	22.9	0.071	1.3	3.9	0.8
258	18.0	0.058	1.3	3.9	0.8
259	19.9	0.040	1.2	4.8	0.8
260	24.9	0.057	1.2	4.7	0.7
261	17.3	0.051	1.3	4.4	0.8
262	19.4	0.061	2.4	4.8	0.7
263	27.0	0.053	1.2	4.0	0.8
265	19.3	0.069	1.3	4.9	0.8
269	20.4	0.071	1.5	4.0	0.9

TABLE 8

Turbidity Means at Station 256
Compared to Rest of Harbour (JTU)

Year	Station 256	Other Stations Mean	S.D.
1968	50	19	5
1969	28	15	5
1970	33	13	3
1972	5.1	4.4	0.5

Note: Turbidity was measured in 1968-69 by the Hamilton Municipal Laboratories using a Lumetron Model 450 Colorimeter, and in 1970 using a Photovolt colorimeter.

1972 data was obtained by MOE using a Hach Model 2100 turbidimeter.

As the JTU is defined using a Jackson trubidimeter, and intercalibration of other instruments is difficult at low turbidity levels, the above data do not indicate a trend between 1970 and 1972. Only the higher turbidity at station 256 compared to the rest of the harbour is indicated.

TABLE 9

Nutrient Loadings (kg/day)

Map I.D.	Outfall or Intake	Ammonia (as N) Mean	Ammonia (as N) SD/mean	Nitrate (as N) Mean	Nitrate (as N) SD/mean	Total Phosphorus (as P) Mean	Total Phosphorus (as P) SD/mean
A	Stelco Intake #2	-6770	92%	-2760	33%	-224	57%
B	Stelco S. Open Cut Sewer	7060	97%	470	35%	43	37%
C	Stelco N. Trunk Sewer	1620	75%	500	31%	43	37%
D	Stelco Intake #1	-670	66%	- 410	31%	- 23	52%
E	Stelco #3 Open Hearth Sewer	780	82%	310	73%	27	39%
F	Stelco 148" Plate Mill	180	104%	130	31%	8	52%
G	Ottawa St. Slip	5040	50%	2150	30%	320	36%
H	Dofasco raw water intake	-2900	56%	- 890	65%	-112	38%
I	Dofasco 3	4210	60%	310	32%	124	111%
J	Stelco #2 Rod Mill Parkdale Works	10	72%	6	112%	3	76%
K	Hamilton WPCP	2350	35%	24	--	970	12%
L	Skyway WPCP	60	144%	280	57%	110	53%
Total		10,970		120		1290	

Note: 1. Negative loadings are intakes.

2. Stelco (E. side lagoon, HCl regen. and cold mill, hot strip mill, heavy gauge shear line), Dofasco (lagoon, Ottawa St. sewer), C.I.L. (total plant less service water intake).

3. Dofasco (coke oven by-products, boiler house discharge, silicon steel).

TABLE 10

1967 Storm Sewer Nutrient Loadings (Kg/day)

Storm Sewer	Ammonia (as N)	Total Phosphorus (as P)
Wellington Street	50	53
Kenilworth Avenue	218	30
Strathearne Avenue	300	80

Above figures calculated from flow and concentration data contained in OWRC, 1967.

TABLE 11

SEASONAL TRENDS OF SURFACE MEANS IN 1972

	Mar. 29	Apr. 28	July 21	July 25	Aug. 1	Aug. 6-7	Aug. 14	Aug. 21	Aug. 29	Sept. 5-8	Sept. 13-14	Sept. 19-20	Sept. 25	Oct. 4-5	Oct. 10	Oct. 18	Oct. 24	Oct. 31	Nov. 9	Nov. 15
NH_3(N)	3.9	5.8	2.4	2.4	1.7	1.7	2.4	2.1	1.5	1.5	-	-	1.6	2.0	1.8	1.5	1.1	0.2	1.0	1.3
Tot.Kjel. Nit. (N)	3.9	5.5	3.2	3.5	2.9	2.7	3.3	2.9	3.0	2.2	2.2	2.2	2.9	2.7	2.4	2.1	2.8	0.9	1.7	1.8
NO_3(N)	1.2	0.8	1.7	2.1	1.6	1.7	1.8	1.9	1.9	1.8	1.0	1.5	1.5	1.6	1.0	0.9	2.0	2.5	2.8	1.9
Total PO_4(P)	.09	.07	.08	.09	.09	.07	.08	.08	.08	.06	.10	.08	.11	.09	.08	.07	.15	.07	.09	.06
Soluble PO_4(P)	.01	.02	.02	.02	.03	.02	.03	.01	.03	.02	.05	.03	.04	.02	.01	.01	.04	.02	.02	.02
Chlorophyll a	5	7	20	26	23	21	14	20	20	19	18	28	24	13	24	17	18	11	13	14

Note: All concentrations in mg/l, except chlorophyll a, in ug/l.

Data are means of at least six sampling stations, at 0.2 or 1.5 m. level.

Chlorophyll a data are for depth composite samples.

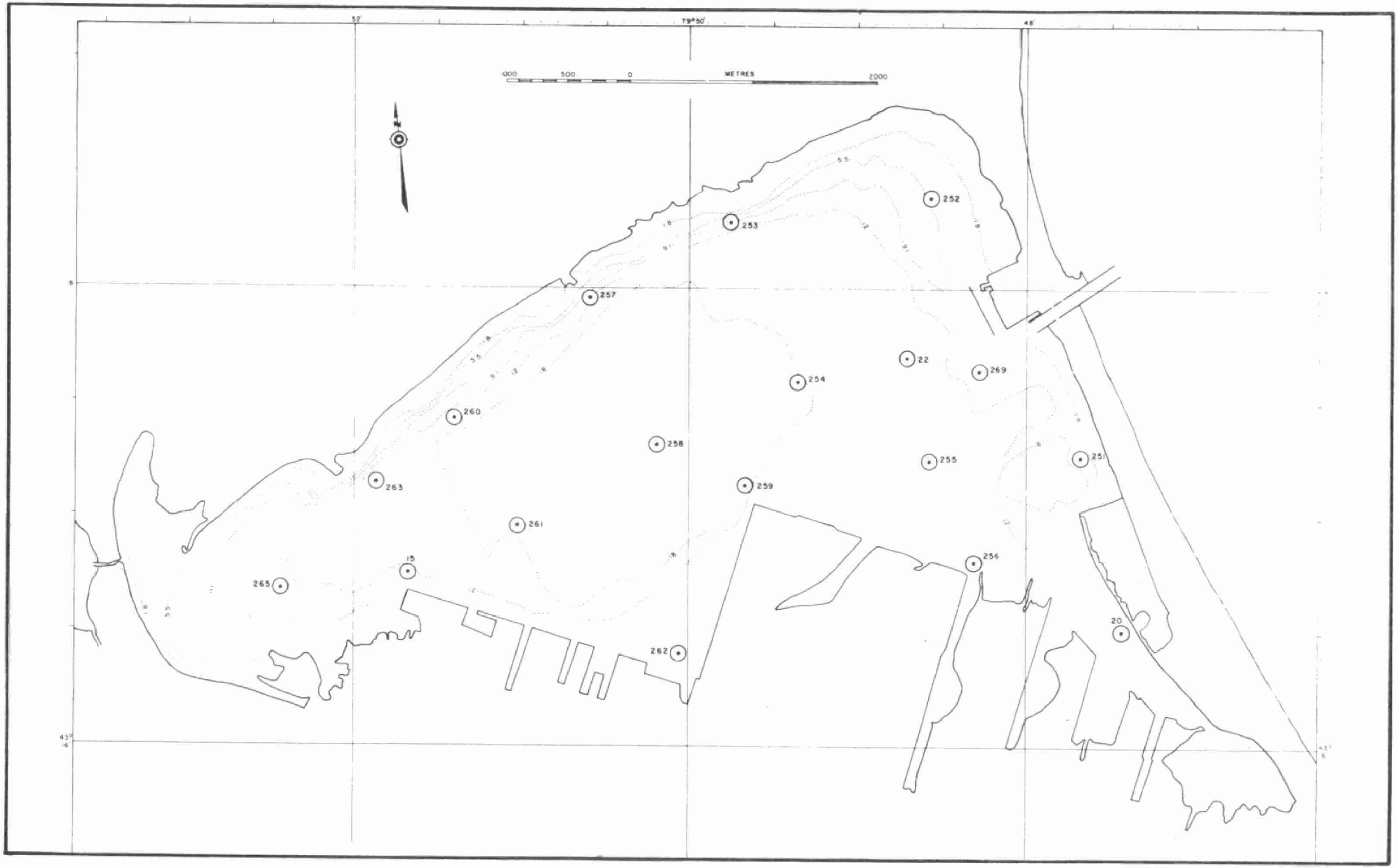
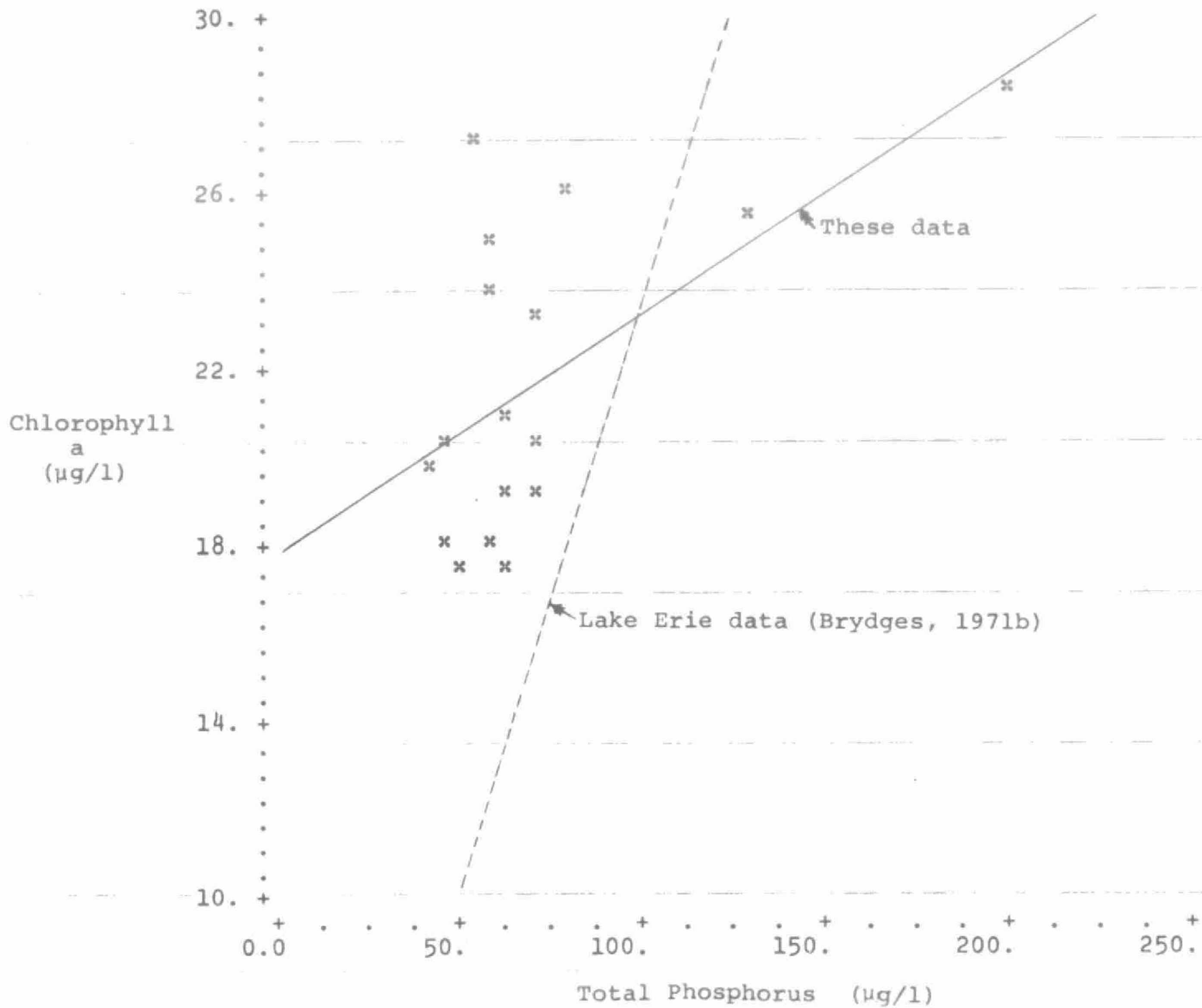


FIGURE 1 : HAMILTON HARBOUR SAMPLING STATIONS

Figure 2

Station averages of chlorophyll a versus total phosphate, Hamilton Harbour, July 21 to October 5, 1972



R25

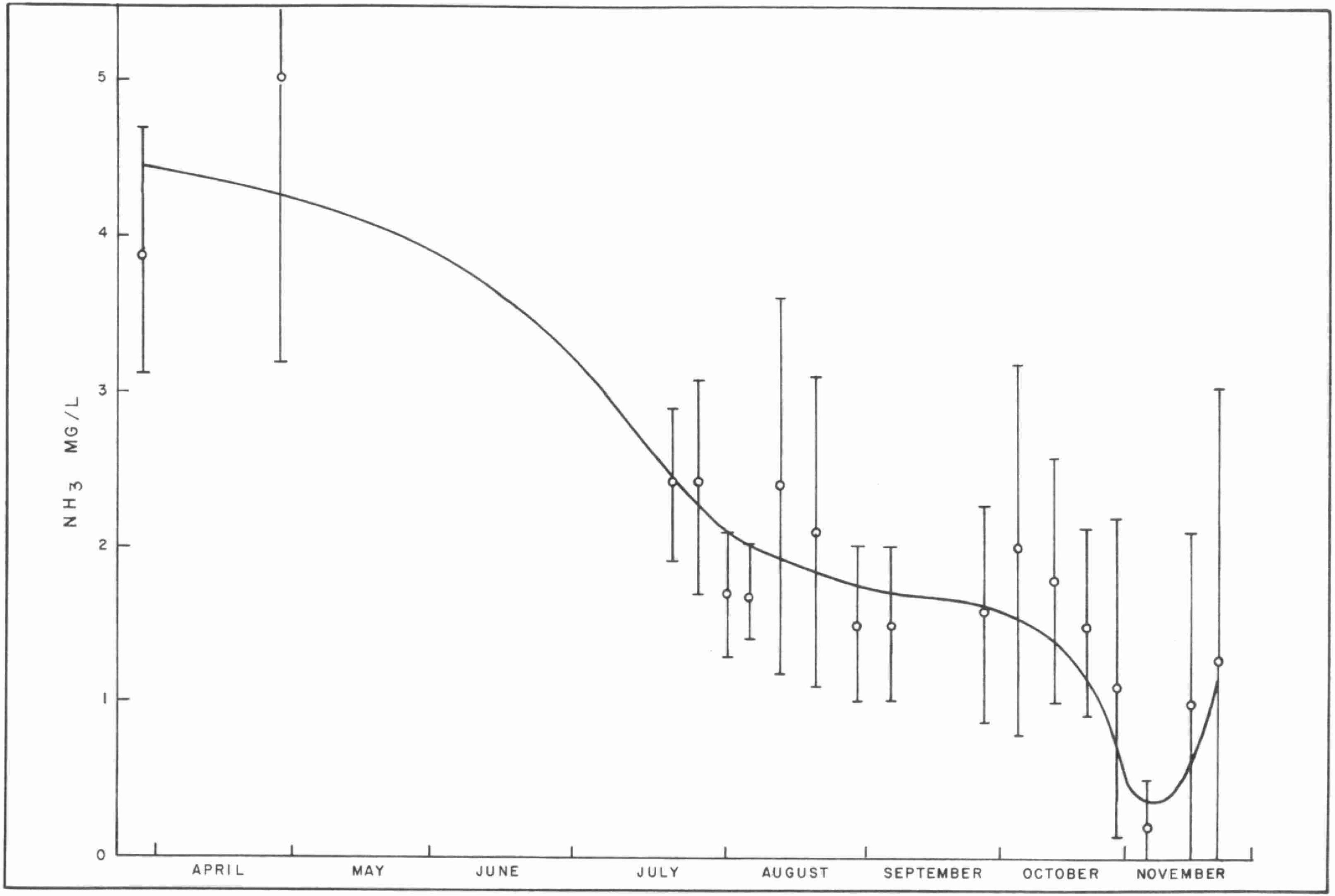


FIGURE 3 : SEASONAL TRENDS OF AMMONIA IN 1972

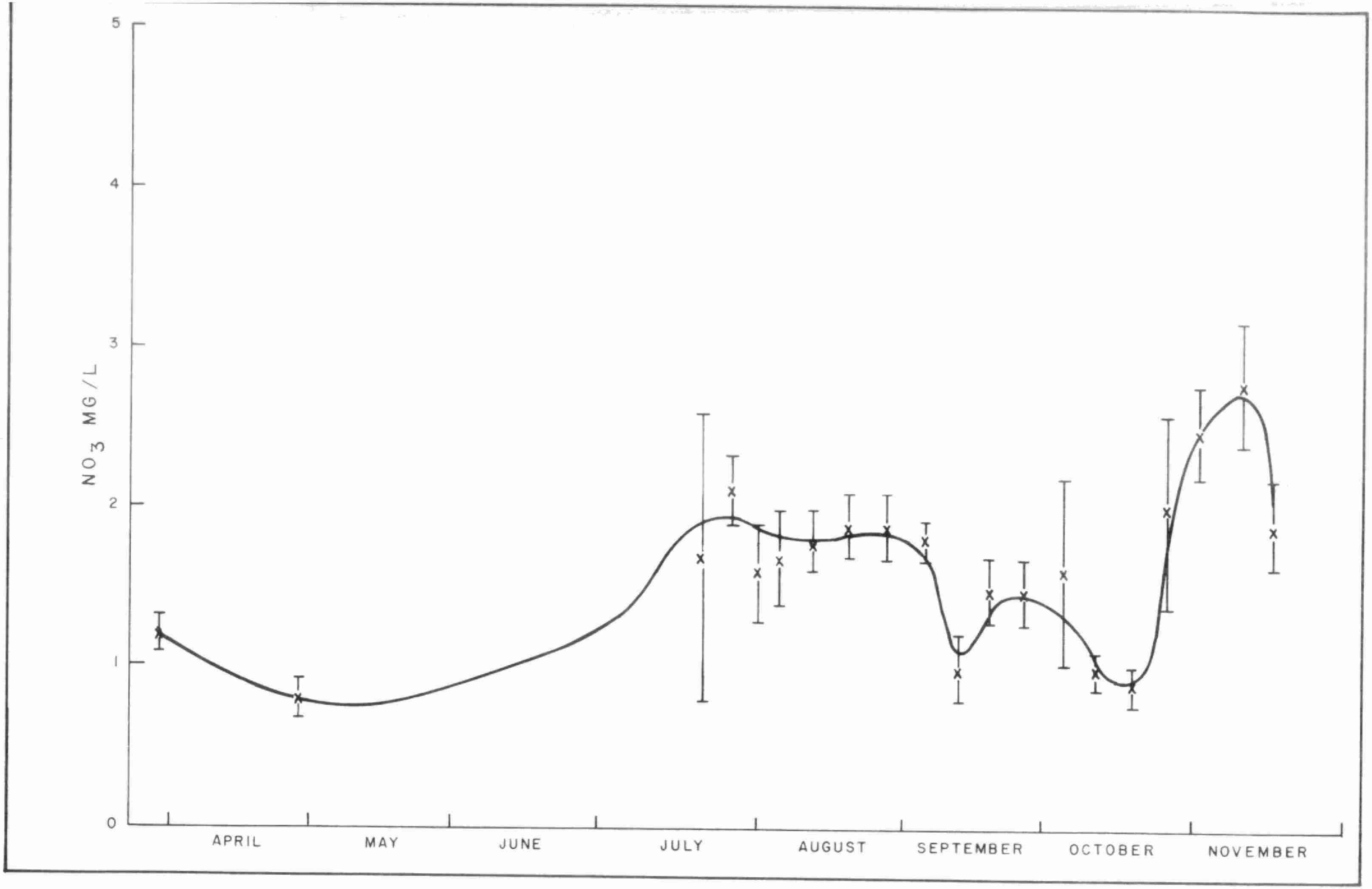


FIGURE 4 : SEASONAL TRENDS OF NITRATE IN 1972

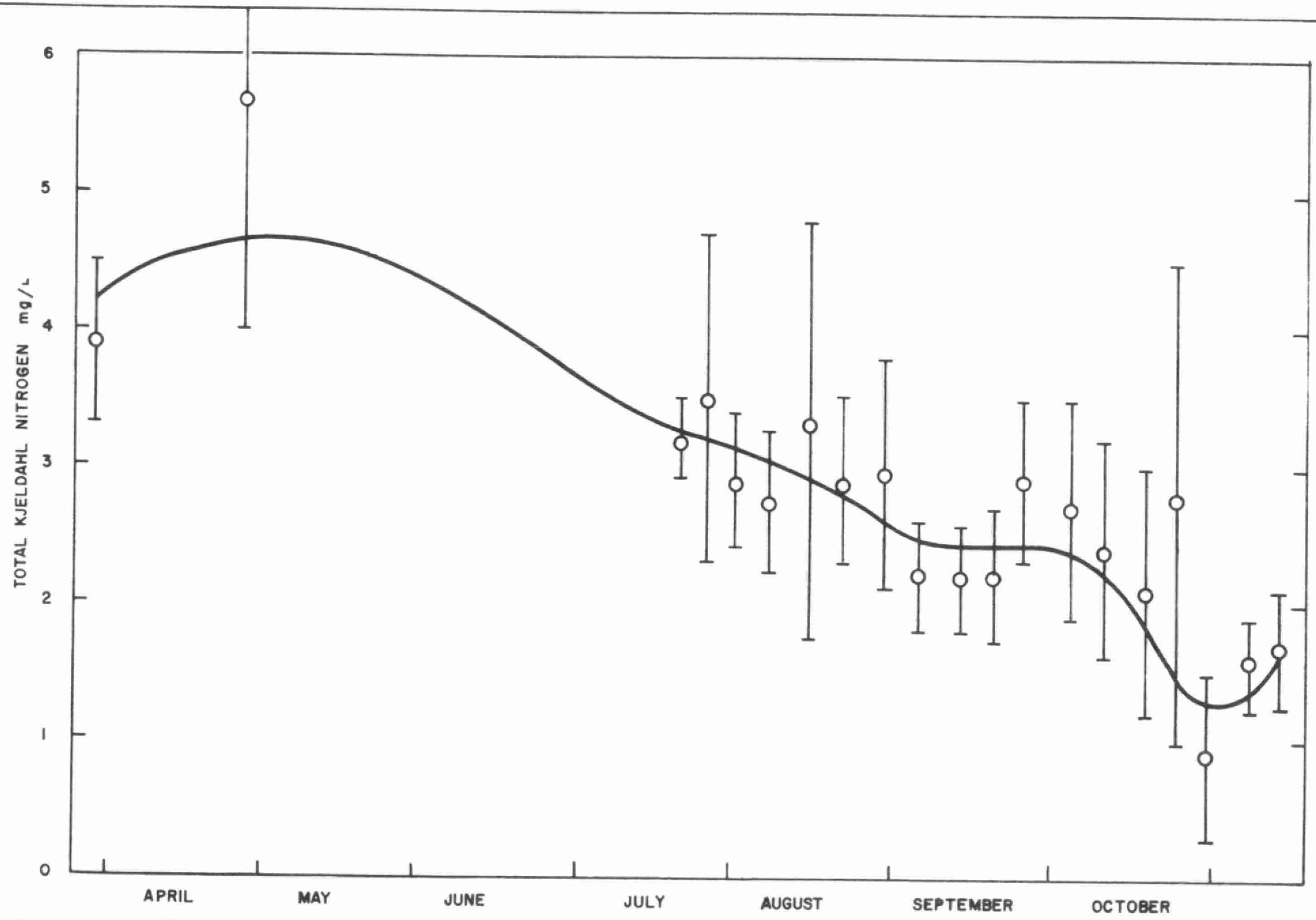


FIG. 5 SEASONAL TREND OF TOTAL KJELDAHL NITROGEN IN 1972

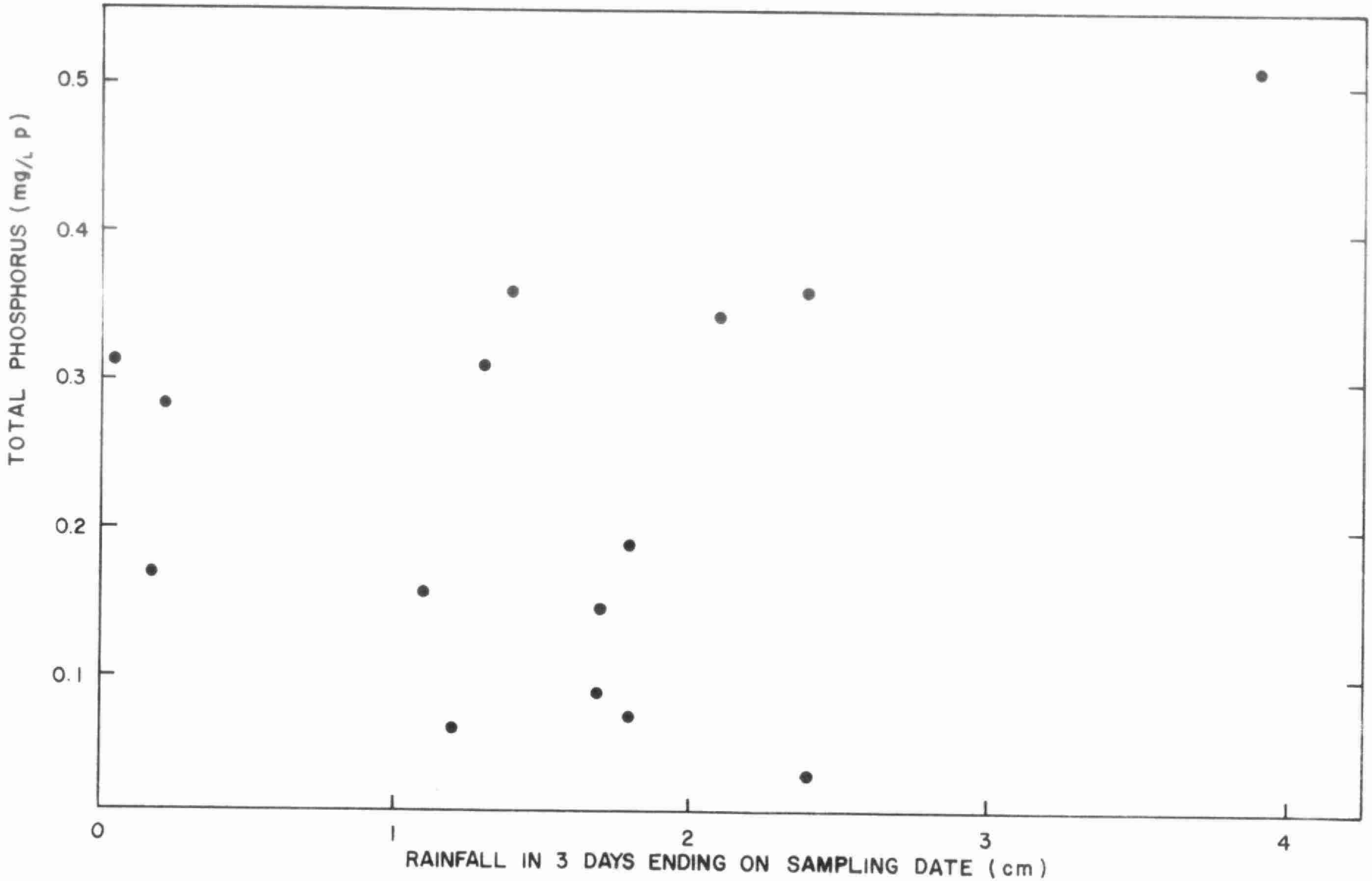


FIG. 6 TOTAL PHOSPHORUS AT STATION 20 AND RAINFALL 1970 TO 1972

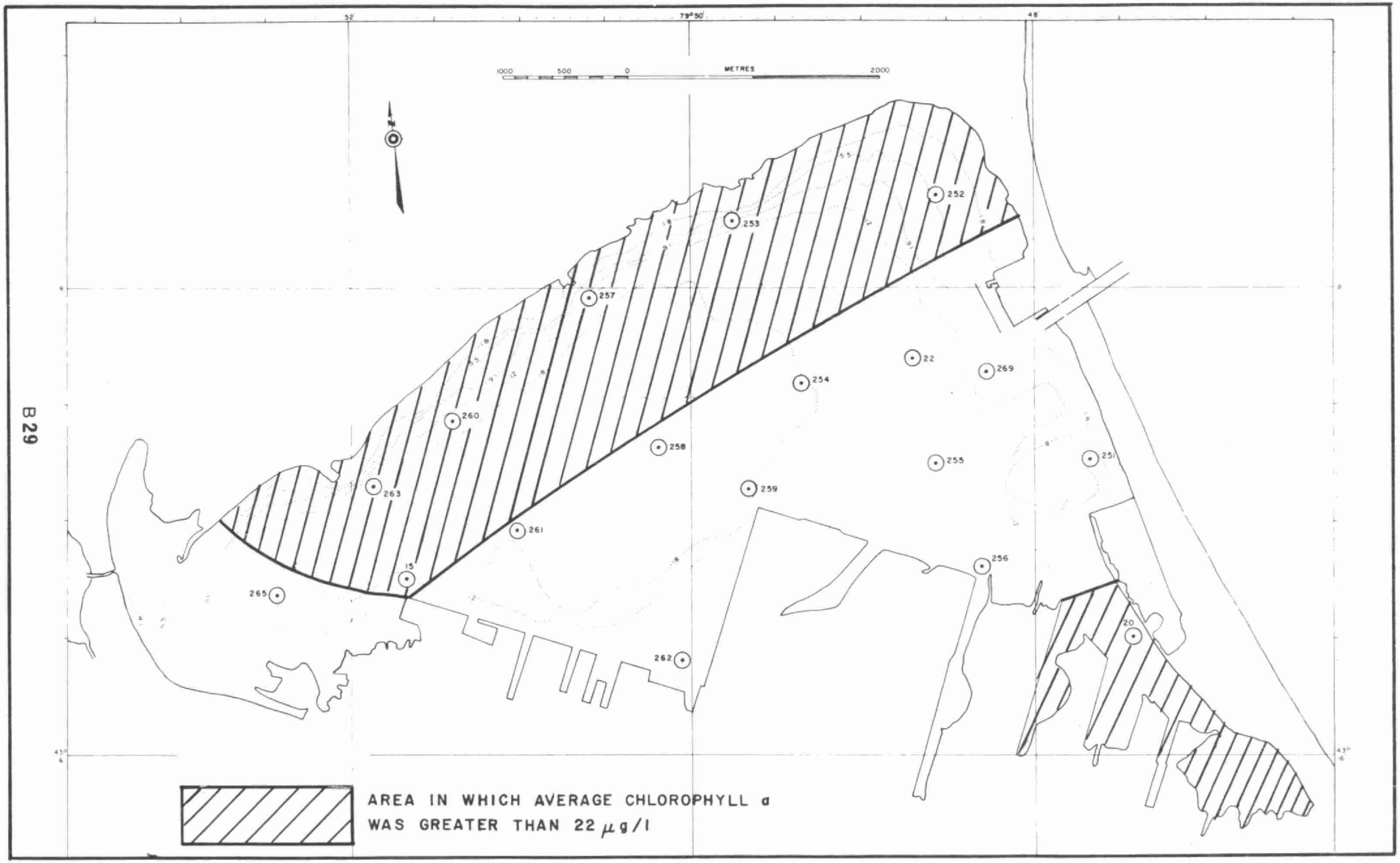


FIGURE: 7 SPATIAL VARIATION OF CHLOROPHYLL a, 1972

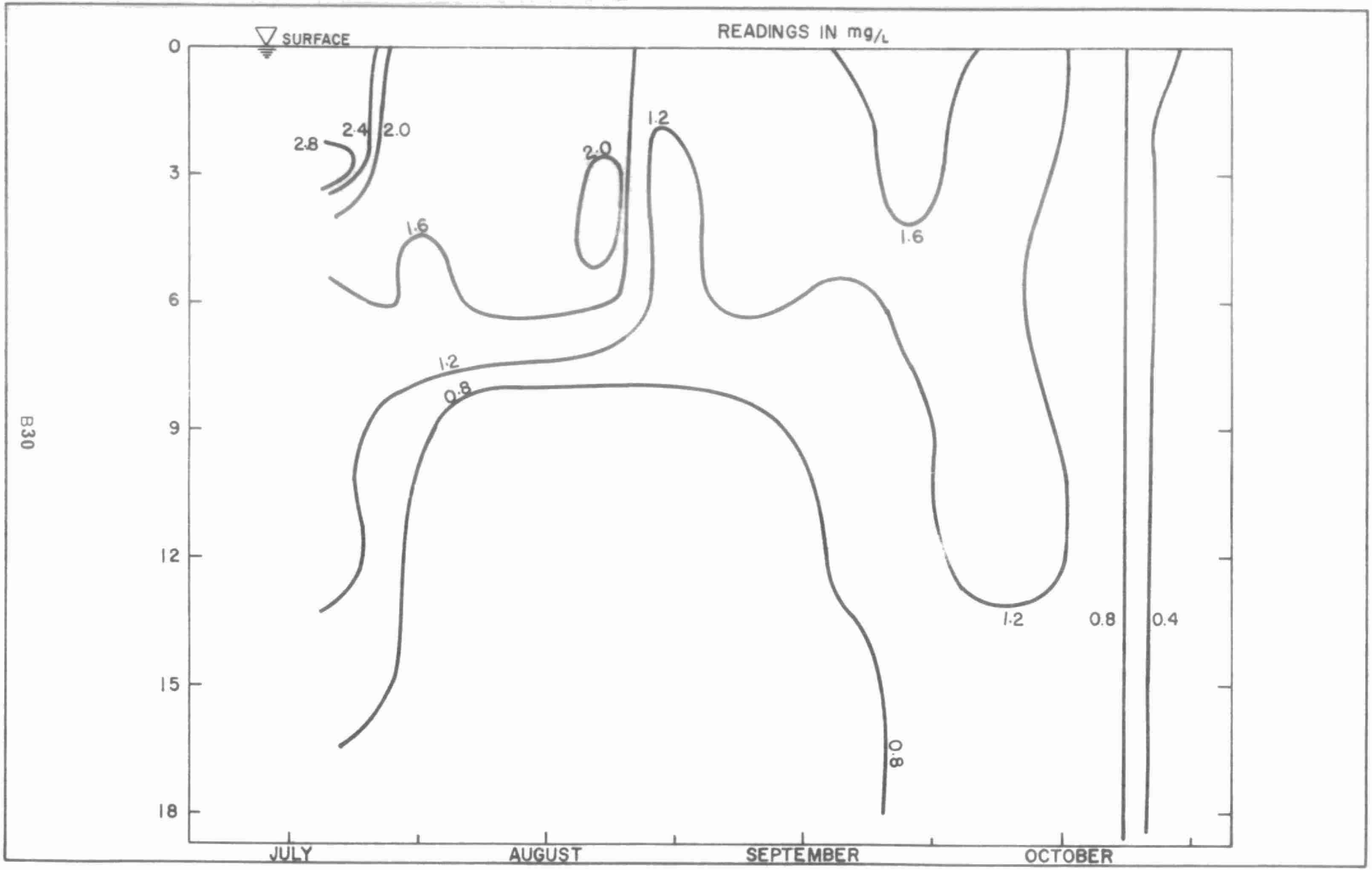


FIG. 8 FREE AMMONIA ISOPLETHS STATION No. 258

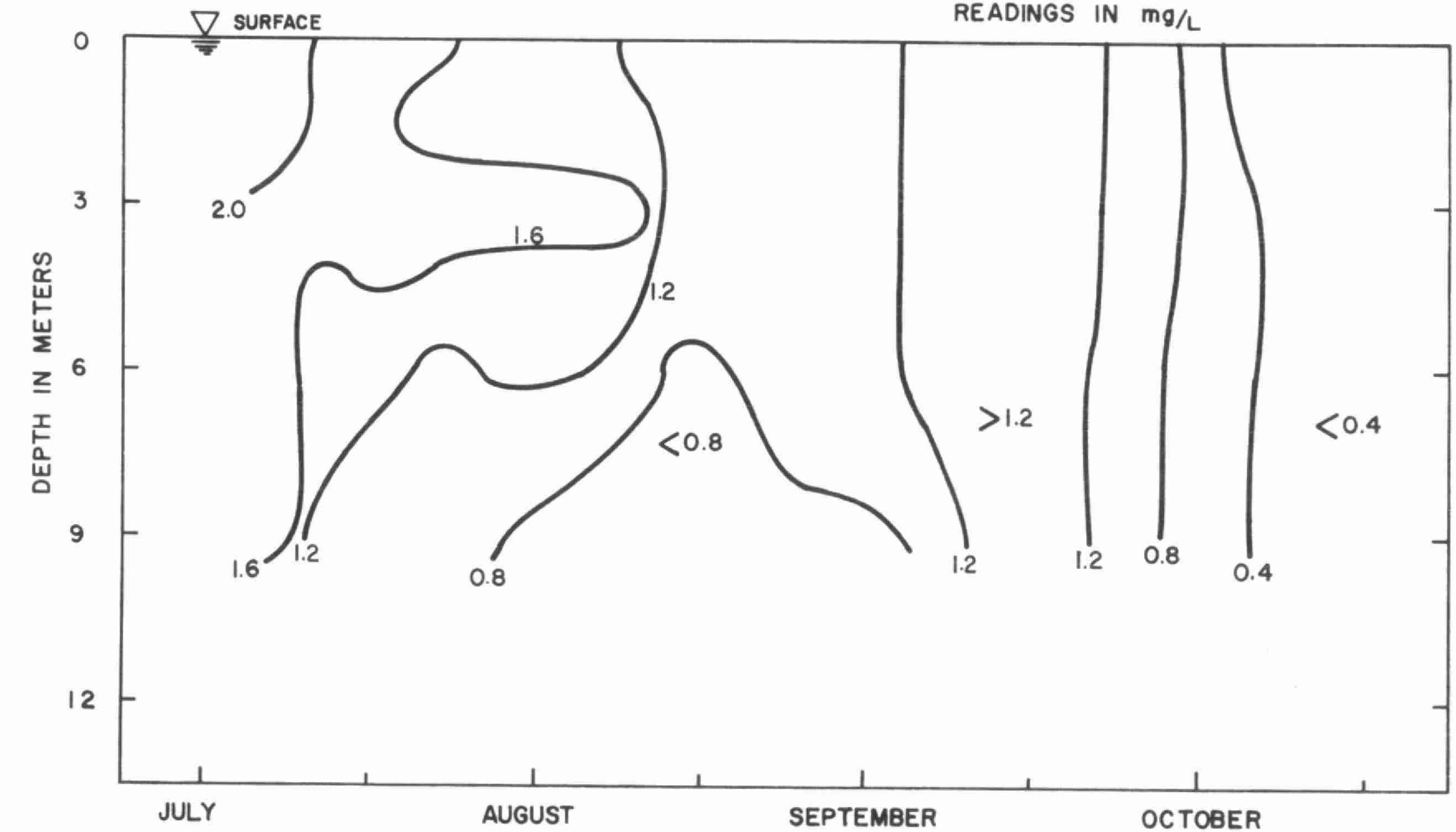


FIG. 9 FREE AMMONIA ISOPLETHS STATION 265

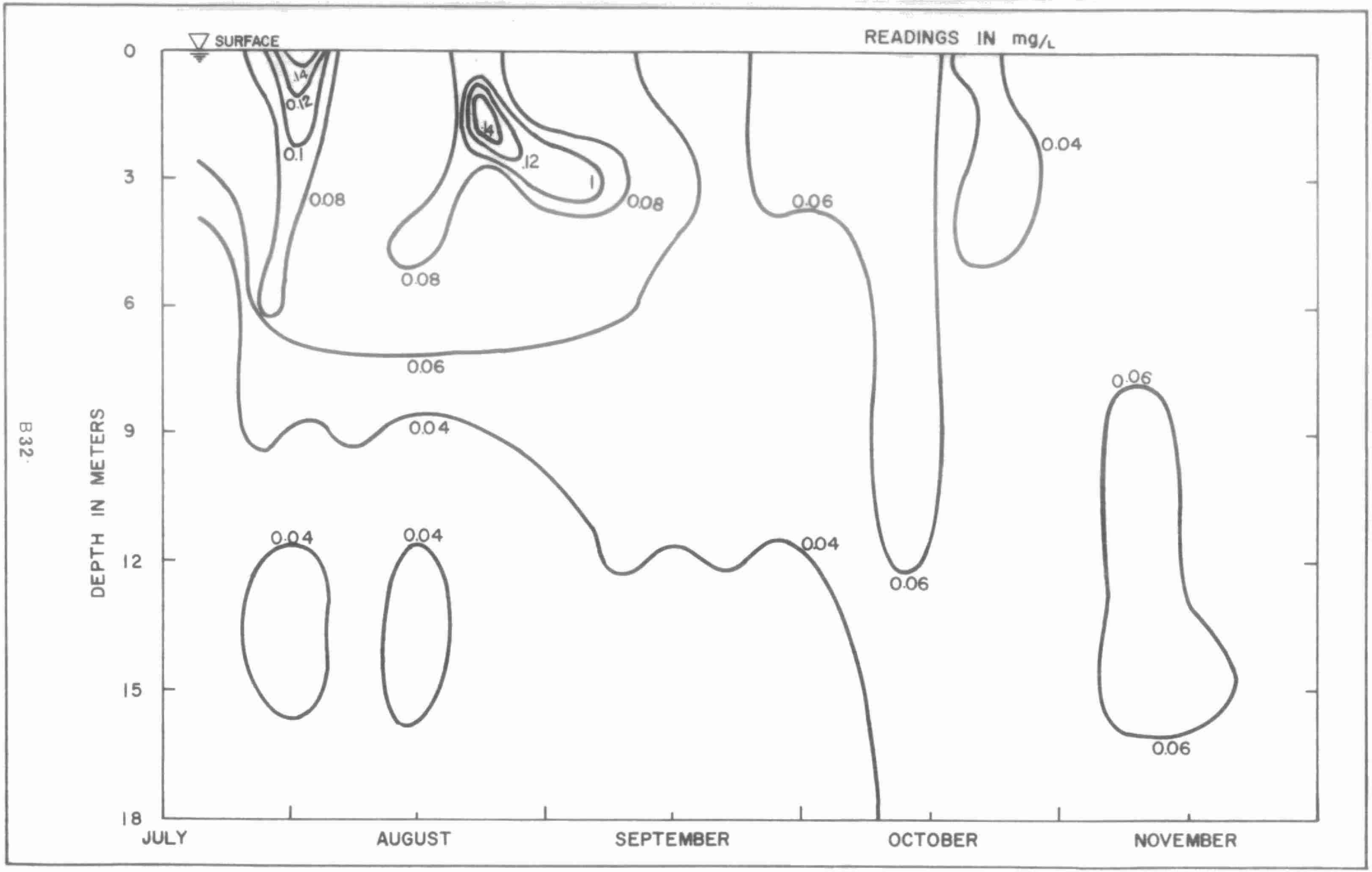


FIG. 10 TOTAL PHOSPHORUS ISOPLETHS STATION No. 258

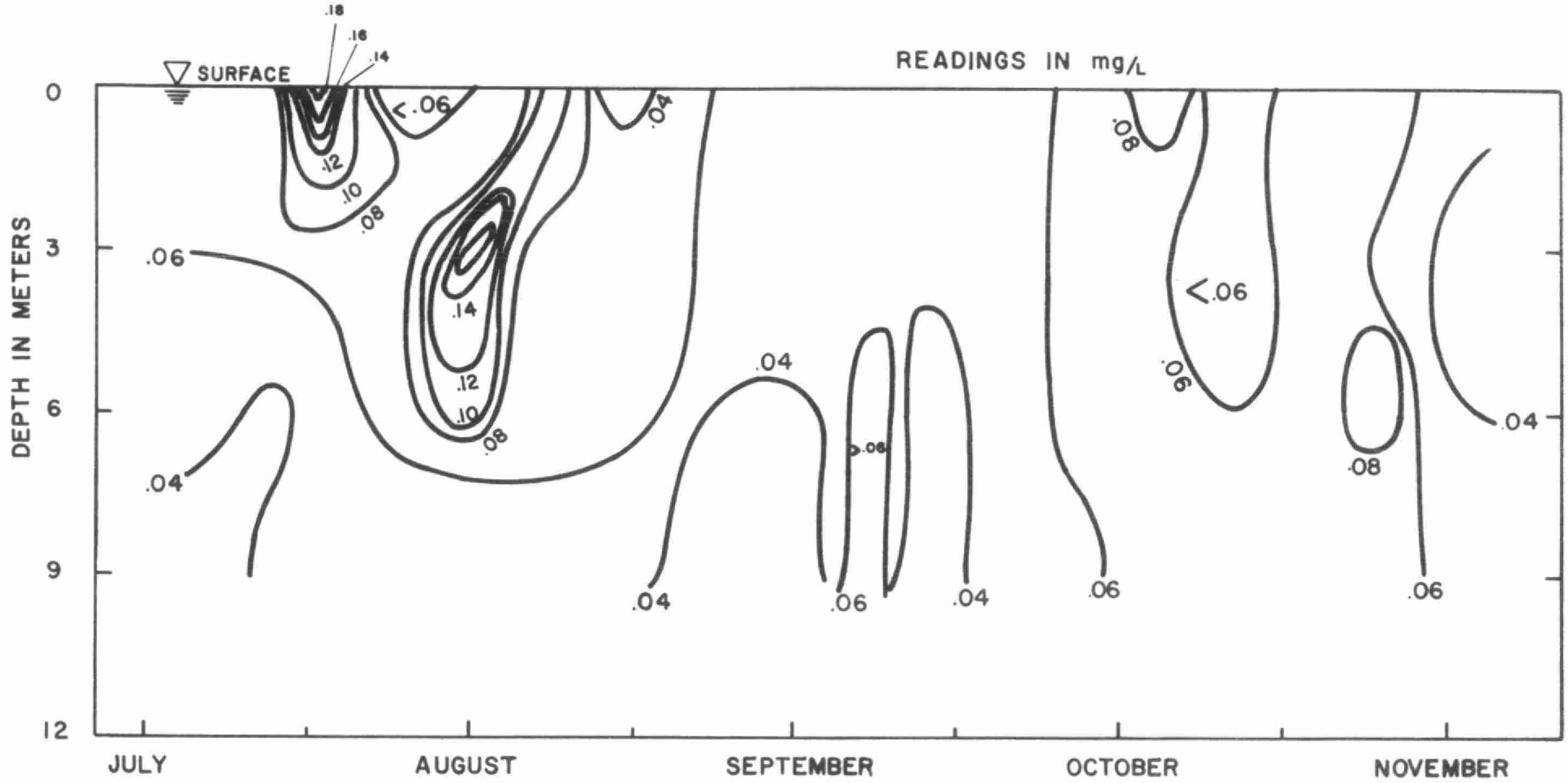


FIG. 11 TOTAL PHOSPHORUS ISOPLETHS STATION No. 265

B 34

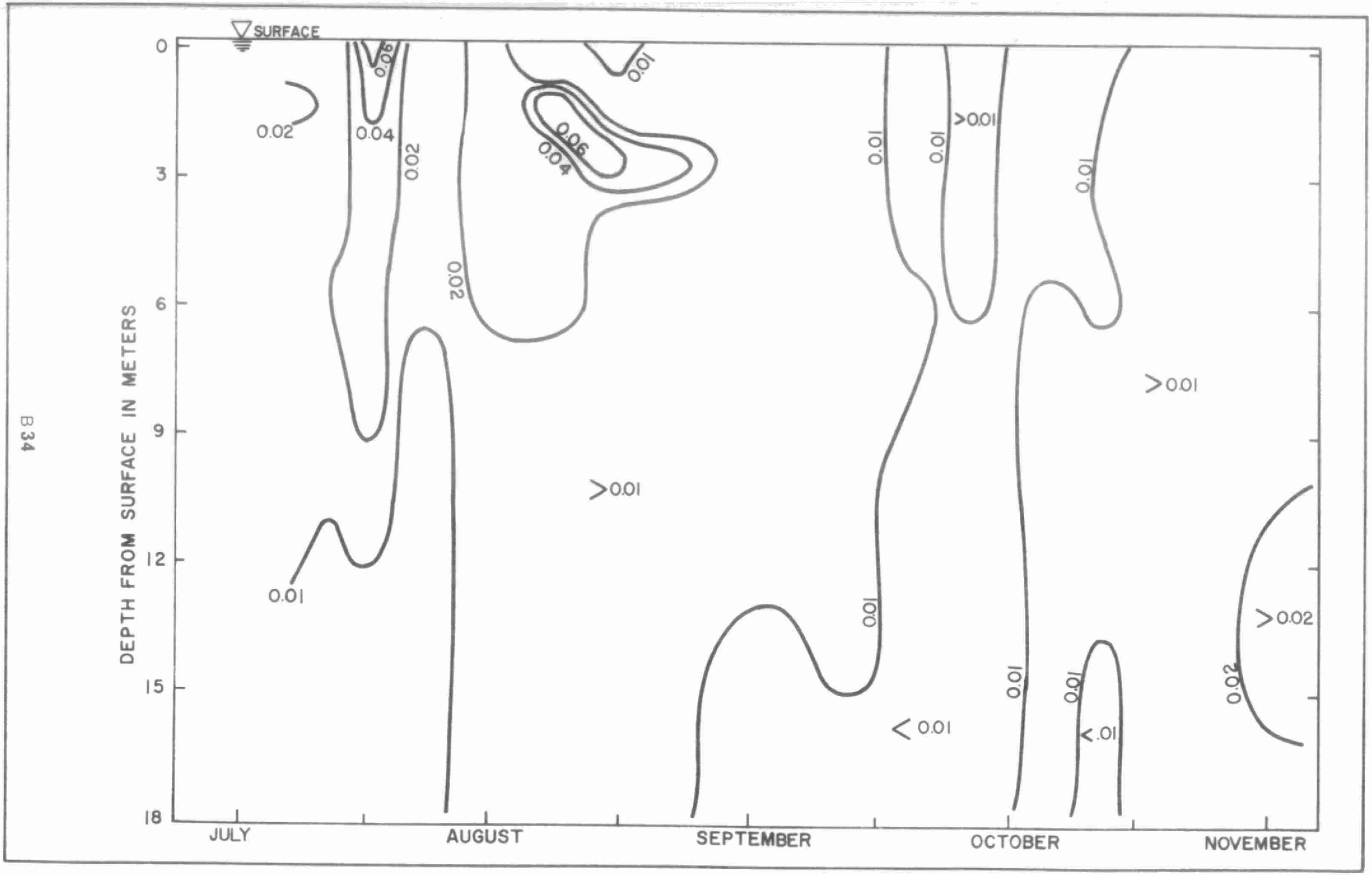
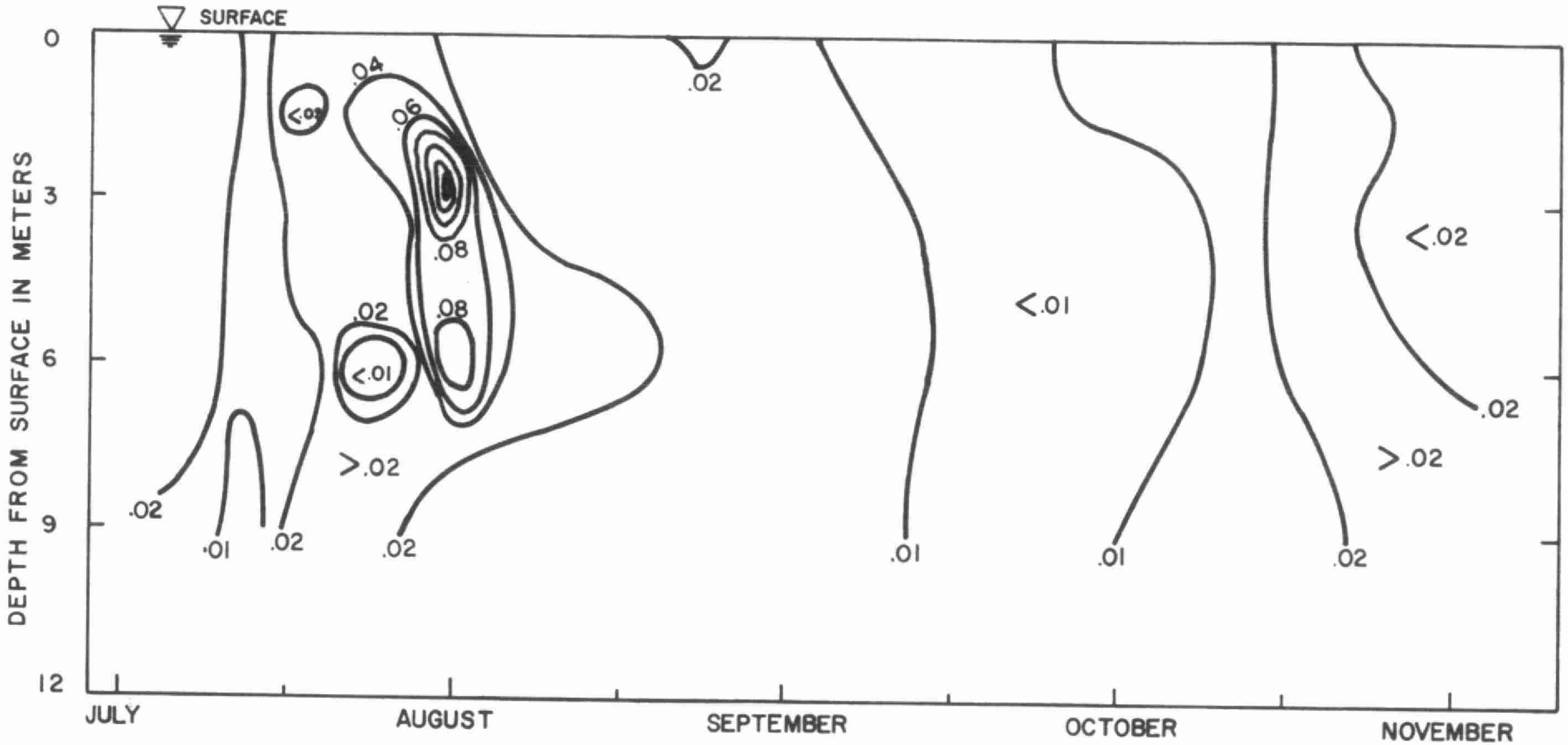


FIG. 12 SOLUBLE PHOSPHORUS ISOPLETHS STATION No. 258



B35

FIG. 13 SOLUBLE PHOSPHORUS ISOPLETHS STATION 265

HAMILTON HARBOUR STUDY

section C

iron-phosphate relationships

HAMILTON HARBOUR STUDY

SECTION C

IRON-PHOSPHATE RELATIONSHIPS

SUMMARY

THE AQUEOUS CHEMISTRY OF IRON AND PHOSPHATES IS DISCUSSED WITH RESPECT TO THE EQUILIBRIA PRESENT IN NATURAL WATERS CONTROLLING THE SOLUBILITY OF THESE ELEMENTS. CONDITIONS FAVOURING INCREASED SOLUBILITY OF IRON INCLUDE LOW PH, LOW DISSOLVED OXYGEN AND THE PRESENCE OF ORGANIC COMPLEXING AGENTS. THE FACTORS THAT CONTROL PHOSPHATE SOLUBILITY ARE COMPLICATED, AND INCLUDE BIOLOGICAL ACTIVITY, THE CHEMICAL FORM OF THE PHOSPHATE, PH AND THE PRESENCE OF METAL IONS. FOR EXAMPLE, CALCIUM IONS PRECIPITATE PHOSPHATE AS HYDROXYLAPATITE, BUT ALSO FORM A SOLUBLE COMPLEX. THE NATURE OF THE PHOSPHATE MATERIAL (ORTHOPHOSPHATE, INORGANIC CONDENSED PHOSPHATE, OR ORGANIC PHOSPHATE), AND THE COMPLEX FORMATION AND HYDROLYSIS KINETICS AND EQUILIBRIA OF THE VARIOUS SPECIES ARE ALSO IMPORTANT. IN NATURAL SYSTEMS, THE BIOLOGICAL UPTAKE AND RELEASE OF PHOSPHATE IS OF FUNDAMENTAL IMPORTANCE IN DETERMINING THE PHOSPHATE CYCLE. ALTHOUGH FERRIC IONS ARE PRECIPITATED BY PHOSPHATE AS FERRIC PHOSPHATE, THIS COMPOUND IS MORE SOLUBLE THAN FERRIC HYDROXIDE AT A PH ABOVE 4, AND HYDROXYLAPATITE AT A PH ABOVE 6 AND A CALCIUM HARDNESS OF 100 MG/L $CaCO_3$.

SOLUBLE PHOSPHATE CONCENTRATIONS OBSERVED IN 1972 ARE INFLUENCED BY THE PRESENCE OF CONDENSED PHOSPHATES, ORGANIC PHOSPHATES, METAL COMPLEXES AND FINELY DIVIDED PARTICULATE MATTER (WHICH CAN PASS THROUGH THE FILTER USED IN THE ANALYSIS). IRON IS PRESUMABLY PRESENT AS FINELY DIVIDED SUSPENDED FERRIC HYDROXIDE AND SOLUBLE ORGANIC COMPLEXES, ALTHOUGH DATA FOR THE LATTER ARE NOT AVAILABLE. AT A FEW POINTS IN THE HYPOLIMNION IN LATE SUMMER, DISSOLVED OXYGEN LEVELS WERE LOW ENOUGH TO PERMIT THE PRESENCE OF SOLUBLE FERROUS IRON.

IF IRON LOADINGS ARE REDUCED WITHOUT CHANGING THE PHOSPHATE LOADINGS, NO CHANGES IN PHOSPHATE CONCENTRATIONS WOULD BE THEORETICALLY EXPECTED DUE TO HYDROXYLAPATITE PRECIPITATION, HOWEVER, AS THE KINETICS OF THIS PROCESS ARE EXTREMELY SLOW, AN INCREASE IN PHOSPHATE CONCENTRATION WOULD LIKELY OCCUR. IF PHOSPHATE LOADINGS ARE REDUCED WITHOUT REDUCING IRON LOADINGS, THE ONLY CHANGE WILL BE A DECREASED AMOUNT OF ADSORBED PHOSPHATE IN THE SEDIMENTED FERRIC HYDROXIDE.

HAMILTON HARBOUR STUDY

IRON-PHOSPHATE RELATIONSHIPS

Introduction

The discharge of phosphorus into lakes and rivers is an important factor in the cultural eutrophication of our water resources. Increased phosphorus concentration results in increased primary productivity, which in turn, will cause depletion of dissolved oxygen in the hypolimnion as a result of oxidation of organic material. Also of importance are the redox conditions existing at the sediment surface; when the redox potential drops to a sufficiently low value, exchange processes result in the release of certain substances to the water, such as ferrous iron and phosphate (Mortimer, 1941). The result is an increased supply of nutrients to the biological community and accelerated eutrophication, a cycle which is broken only by the removal of phosphate as an unreactive sediment or its removal from waste input streams.

The concentrations of phosphate in the harbour are generally low considering the loadings emanating from the municipal pollution control plant. As the phosphates are discharged in closed proximity to the industrial iron discharges, it is reasonable to assume that phosphates are fixed by the iron and precipitated. Pollution abatement programs will reduce both the amount of iron and phosphate discharged. Are water quality problems likely to occur if the two programs are not co-ordinated?

In this bulletin, it is shown that reduction of phosphate loadings should have no effect on the observed iron concentrations in the bay. If iron loadings are reduced, the soluble phosphorus will be unchanged or may show a decrease because of reduced complex formation.

Using the available redox and equilibrium data, solubility values have been calculated for various forms of iron (Hutchinson, 1957, p. 705). Some figures thus obtained are given in Table 1. It is seen that under normal conditions, the activity of ferric ion is much too small to be detected analytically; for a detectable amount of ferric iron to be found in solution, the pH must be below about 4. Ferrous iron is undectable at a redox potential of 0.25 volt and a pH greater than 7; this redox potential corresponds to a dissolved oxygen concentration of about 0.5 mg/l (Mortimer, 1941). The lower redox potentials, at which ferrous ion is detectable, are only found under anoxic conditions, or within the sediments. Therefore, under normal conditions, no significant concentration of ionic iron can be expected to occur.

If the dissolved oxygen should drop below 0.5 mg/l in the hypolimnion, ferrous iron in solution will appear. This is oxidized to colloidal ferric hydroxide at a depth where sufficient dissolved oxygen is found, producing

increased color and turbidity. Upon overturn in the fall, any ionic ferrous iron present is oxidized and precipitated, although this oxidation may not occur immediately (Mortimer, 1941). In general, some finely divided ferric hydroxide is retained in suspension at all times, by current action.

Solubility of Ionic Fe

Under oxic conditions, iron is always present naturally in the trivalent state which undergoes hydrolysis and precipitation as ferric hydroxide ($Fe(OH)_3$) according to the reactions.

$$Fe^{3+} + H_2O \rightleftarrows FeOH^{2+} + H^+ \qquad \text{Log } K_1 = -2.2 \tag{1}$$

$$FeOH^{2+} + H_2O \rightleftarrows Fe(OH)_2^+ + H^+ \qquad \text{Log } K_2 = -4.7 \tag{2}$$

$$Fe(OH)_2^+ + H_2O \rightleftarrows Fe(OH)_3 + H^+ \tag{3}$$

$$Fe(OH)_3 + H_2O \rightleftarrows Fe(OH)_4^- + H^+ \tag{4}$$

Equilibrium data for these and other reactions are for 25 degrees and zero ionic strength (Sillen and Martell, 1964). Data for reactions 3 and 4 were not available.

In the presence of solid ferric hydroxide, the distribution of the various ferric ion species is controled by the equilibrium constants for the above reactions and the solubility product constant for ferric hydroxide.

$$S_3 = a_{Fe^{3+}} \, a^3_{OH^-} = 10^{-36} \tag{5}$$

Iron may occur in two oxidation states, ferrous (Fe^{+2}) and ferric (Fe^{+3}). The concentrations of ferrous and ferric ions are related by the Nernst equation.

$$E = E^o + \frac{RT}{F} \ln \frac{a_{Fe^{3+}}}{a_{Fe^{2+}}} \tag{6}$$

where R is the ideal gas constant, F is the Faraday constant, T is the absolute temperature and E^o is the standard redox potential for the ferrous-ferric system ($E^o = 1.011$ v). Although the redox potential is relatively insensitive to changes in the dissolved oxygen content of the water above 1 mg/l, it decreases rapidly as anoxic conditions are approached. Under such conditions, as may occur in the hypolmnion late in summer, iron may dissolve as ferrous ions.

Iron-Organic Complexes

Iron is found in colloidal or true solution associated with organic material such as humates, tartrates, lignates, chlorophyll or other chelates (Hutchinson, 1957; Osborn, 1960). Biochemical utilization of iron is important in the

formation of such complexes. Aquatic plants, algae and lichens all remove iron from either the water or the mud, as required for tissue growth. Upon death, gelatins, tannins and other plant acids are released holding complexed iron in solution. Up to 16.8 mg/l of iron in solution has been reported as a result of organic complexes (Hutchinson, 1957, p. 712).

Although the interaction of iron with organic matter has been much investigated, the nature of the complexes formed remains undefined. (Plumb and Lee, 1973).

Phosphate Solubility and Complex Formation

The usual form of dissolved phosphorus, and indeed, the ultimate product of hydrolysis of all phosphates, is orthophosphoric acid and its anions (H_3PO_4, $H_2PO_4^-$, $HPO_4^=$, PO_4^{3-}). Also present in polluted waters are inorganic condensed phosphates such as pyrophosphate ($H_nP_2O_7^{(4-n)-}$, $0 \leq n \leq 4$), tripolyphosphate ($H_nP_3O_{10}^{(5-n)-}$, $0 \leq n \leq 5$), metaphosphates ($(PO_3^-)n$, $n \geq 3$), and dissolved or colloidal organic phosphates. The latter are a result of biological activity, and can represent 15 to 60 percent of the total phosphorus (AWWA Committee Report, 1970; Rigler, 1964). That much of these phosphates is actually colloidal is shown by the fact that the amount of soluble organic phoshpate is a function of the nature of the filter used for removing particulate or sestonic material (Rigler, 1964). Organic phosphates containing C-P bonds are highly resistant to hydrolysis, and are not detected in the usual soluble phosphate analysis, in which the molybdenum blue colorimetric method is applied directly to the filtrate, without acid hydrolysis (Brydges, 1971).

The solubility of orthophosphates in natural water is generally controlled by calcium ions, which result in the precipitation of hydroxylapatite, $Ca_5OH(PO_4)_3$, whose solubility product constant is given by the equation

$$S_H = a^5_{Ca2+} \quad a^3_{PO_4^{3-}} \quad a_{OH-} = 10^{-55.6} \qquad (7)$$

Combination of this solubility product with the acid ionization constants of phosphoric acid allows a definition of the maximum soluble orthophosphate as a function of pH and calcium ion concentration (AWWA Committee Report, 1970). At a calcium ion concentration of 40 mg/l Ca, or a calcium hardness of 100 mg/l $CaCO_3$, soluble orthophosphate concentration decrease rapidly with increasing pH, being about 2 mg/l P at pH 6 and 0.01 mg/l P at pH 7.

However, the solubility of phosphate in the presence of calcium is influenced by complex formation, according to

$$Ca_5OH(PO_4)_3 + 4H^+ \rightleftarrows 2\ Ca^{2+} + 3\ CaHPO_4(aq) + H_2O \quad K_8 = 3 \times 10^2 \quad (8)$$

In this equation, $CaHPO_4(aq)$ represents the complex; at a pH of 7 and a calcium concentration of 40 mg/l Ca, its concentration is approximately the

same as that of the uncomplexed phosphate. Magnesium also forms a similar complex, $MgHPO_4(aq)$, which should contribute to phosphate solubility.

The solubility of condensed phosphates is also influenced by similar reactions. In the case of calcium pyrophosphate ($Ca_2P_2O_7$), the solubility product constant is defined as

$$Spp = a^2_{Ca^{2+}} \; a_{P_2O_7{}^{4-}} = 10^{-7.9} \tag{9}$$

Complex formation also occurs according to the reaction

$$Ca^{2+} + HP_2O_7{}^{3-} \rightleftarrows CaHP_2O_7{}^{-}, \; K_{10}=1 \times 10^{-2} \tag{10}$$

At a pH of 7 and a calcium concentration of 40 mg/l Ca, the maximum soluble pyrophosphate concentration is about 1.2 mg/l as P, of which more than 50 percent is in the complexed form.

Hydrolysis of Condensed Phosphates

Hydrolysis of condensed phosphates is thermodynamically favorable, producing orthophosphate as the final product. However, the kinetics of this reaction are complicated, being influenced by temperature, pH, bacterial activity and metal ion complexing, among other factors. In general, the more polluted a natural system is, the faster is the hydrolysis rate. For example, the rate constant for hydrolysis of pyrophosphate at 25 degrees C in distilled water is 6.5×10^{-8} min^{-1}. In sterile Lake Mendota water, it is 6.1×10^{-5} min^{-1} (Clesceri and Lee, 1965). In the presence of microorganisms, enzymatic processes result in even greater hydrolysis rates.

Ferric Phosphate Equilibria

Ferric phosphate is a slightly soluble salt, whose solubility is described by the solubility product constant

$$Sp = a_{Fe^{3+}} \, a_{PO_4{}^{3-}} = 10^{-23} \tag{11}$$

The equilibrium between ferric phosphate and hydroxide may be represented by the equation

$$Fe(OH)_3 \; (s) + PO_4{}^{-3} \rightleftarrows FePO_4 \; (s) + 3OH^- \tag{12}$$

If the activities of solid phases are considered to be unity (as is done in defining solubility product constants), the equilibrium constant K_{13} for the above process is equal to

$$K_{13} = \frac{a^3{}_{OH^-}}{a_{PO_4{}^{3-}}} = \frac{S_3}{S_p} = 10^{-13} \tag{13}$$

Equation (12) may be related to other pH values by introducing the ionization constants for phosphoric acid and water; for example, at pH values near 7 to 9, reaction (12) may be represented as

$$Fe(OH)_3 + HPO_4^{2-} \rightleftarrows FePO_4^{+} + 2OH^- + H_2O \qquad (14)$$

$$K = \frac{S_3}{S_p} \cdot \frac{K_3}{K_w} = 10^{-11} \qquad (15)$$

where K_3 is the third ionization constant of phosphoric acid ($=1 \times 10^{-12}$) and Kw is the ionization constant of water ($=1 \times 10^{-14}$).

The solubility relationship between ferric phosphate and hydroxide is further complicated by the existence of complex ions, for example:

$$Fe^{3+} + HPO_4^{2-} \rightleftarrows FeHPO_4^{+}, \ \log K = 8.3 \qquad (16)$$

Although calculations (AWWA Committee report, 1970) indicate that less than 1 percent of iron and phosphate is complexed at pH5, the situation is different if pyrophosphate is present. Under conditions of total (Fe)=1×10^{-5}M (0.6 mg/l) and total ($P_2O_7^{4-}$)=1×10^{-5} M (0.3 mg/l as P), 99 percent of the pyrophosphate is complexed with ferric iron (AWWA Committee report, 1970).

Using data tabulated by Sillen and Martell (1964), the solubility of various phosphates and of ferric hydroxide has been plotted as a function of pH (AWWA Committee report, 1970). Ferric phosphate is considerably more soluble than ferric hydroxide at pH4, and above pH6, the solubility of phosphate becomes controlled by hydroxylapatite precipitation.

While equilibrium data of this nature are useful in general, caution must be applied in their use. Equilibria will never be completely reached in natural systems for several reasons, such as thermal stratification, biological assimilation, transport of materials by current action, continuous introduction of compounds at outfalls, adsorption and co-precipitation, and slow kinetics of certain reactions. In particular, the biological uptake of phosphate , its sedimentation in the form of dead plankton, and resolution by bacteriological or chemical means at the sediment-water interface are of fundamental importance in the phosphorus cycle (Hutchinson, 1957). For these reasons, computer models of these systems, such as that of Morel and Morgan (1972) are of limited usefulness.

The Situation in 1972

A considerable volume of data was obtained for iron and total and soluble phosphorus in 1972. A selection of the iron data for stations located near Stelco and Dofasco is given in Table 2, and phosphorus data in Table 3. Station locations appear in Figure 1. Data for iron, total organic carbon and chemical oxygen demand are given in Table 4 for outfalls and intakes at Stelco and Dofasco. The average total phosphorus concentration observed

at the major steel company outfalls was 0.1 - 0.2 mg/l and the corresponding soluble phosphorus was below 0.1 mg/l.

The highest iron concentrations were observed at station 20 (mean=1.3 mg/l), although results for station 256 (mean=1.0 mg/l) were frequently higher than station 20. Results at both stations were highly variable (coefficient of variation=1.0). Iron loadings from the municipal sewage plant are not known, but, should naturally be less than those from the steel plants. The highest iron loadings are from the east side lagoon at Stelco and the Ottawa St. sewer at Dofasco, both discharging to the Ottawa St. slip. Consequently, one would expect iron concentrations to be high at station 256. A possible reason for this discrepancy is the formation of iron-pyrophosphate complexes from the pyrophosphate contained in the Hamilton WPCP effluent. This mechanism would, however, require iron to be transported eastward along the shoreline. No correlation exists between the total iron loadings to the Ottawa Street slip and the measured figures at station 256. This is not surprising, considering the high variability of the iron loadings.

As in the case of iron, phosphorus loading data from the Hamilton WPCP are not available. The effect of the Hamilton WPCP on the harbour phosphorus content is shown by the survey data for station 20, which indicate a mean total phosphorus value of 0.21 mg/l for 1972, as compared to a mean of 0.069 mg/l for the entire bay. The variable nature of the loadings from the WPCP results in a coefficient of variation of 0.9 for total phosphorus and 1.3 for soluble phosphorus. Much of the soluble phosphorus present here is presumably condensed phosphates and their complexes, which are gradually hydrolyzed to less soluble orthophosphate, which is precipitated chemically or assimilated biologically.

Neglecting complexes, slow kinetics of hydroxylapatite precipitation, condensed phosphates and organic phosphates, the maximum soluble phosphorus concentration in Hamilton Harbour should be below 0.0001 mg/l P at a 1972 observed average pH of 7.5 and hardness of 180 mg/l $CaCO_3$, assuming that the hardness is entirely due to Ca. That observed soluble phosphorus values are 2 to 3 orders of magnitude higher than this indicates the importance of the above factors. In particular, colloidal matter which may pass through the 2 to 4 u glass fiber filters used in this laboratory (Brydges, 1971) may influence the result. Iron-pyrophosphate complexing should be important, although its contributions will depend upon the kinetics of complex formation.

If iron discharges were reduced without concurrent reduction in phosphate loading, theoretical considerations outlined above would suggest a possible decrease in the soluble phosphorus due to iron-polyphosphate complexing. However, in practice, hydroxylapatite precipitation is so slow that increasing amounts of phosphate are retained either in solution or in fine suspension as iron contents are decreased. For example, Thompson Lake, a much smaller lake with a hardness similar to that of Hamilton Harbour, but a very low iron concentration, has total and soluble phosphorus values of 0.25 and 0.08 mg/l compared to Hamilton Harbour average figures of 0.08 and 0.025 mg/l. This is a good example of the failure of natural systems to reach chemical equili-

brium for reasons already stated. Therefore, total and soluble phosphorus concentrations in Hamilton Harbour will most likely increase should iron, but not phosphorus, loadings be reduced.

According to the solubility data presented earlier, iron should be precipitated as ferric hydroxide. However, co-precipitation of phosphate by ferric hydroxide can be expected to occur (AWWA Committee Report, 1970); indeed, this co-precipitation renders the determination of a solubility product constant difficult. The nature of iron in the sediments is therefore, expected to be something like $Fe(H_2PO_4)n\ (OH)^{3-n}$ or $Fe\ (HPO_4)\ n/2\ (OH)^{3-n}$ where n may vary between 0 and 3. The effect of reducing phosphate discharge would merely be to reduce the value of n in the above formulas, without any increase in dissolved iron concentration. If the sediments are sufficiently crystalline in nature, the form of iron present could be determined by X-ray analysis; however, amorphous precipitates may be present. Chemical analysis will indicate the amount but not the nature of iron present.

At station 256 (Ottawa Street slip), dissolved oxygen values below 0.5 mg/l occurred regularly during August near the bottom (12 meter depth), with anoxic conditions occurring on the 14th. In September, the dissolved oxygen at this point gradually increased. Although these data correlate with iron contents of about 1 mg/l in August and a decrease in September, iron contents above 1 mg/l were frequently found at station 20, where the dissolved oxygen averaged 5 mg/l and was below 1 mg/l only on October 24. Dissolved ferrous iron was undoubtedly present at station 256, but the iron at station 20 must have been present in particulate (or complexed) form. Dissolved oxygen below 0.5 mg/l was seen frequently in the hypolimnion at station 258 in the center of the bay, with zero being reached on August 14 and August 29. At other stations, dissolved oxygen values below 0.5 mg/l were seen only very infrequently or not at all, although such values did occur at least once at nine of the 17 stations.

Assuming that the dissolved oxygen content does not drop low enough ($<$ 0.5 mg/l) to permit the formation of an appreciable amount of ferrous iron, the only mechanism in which iron will be solubilized is the formation of organic complexes. That this may occur is shown by some studies on Lake Mary, Wisconsin (Plumb and Lee, 1973). In this lake, which has an iron concentration of 0.75 mg/l and TOC 15 mg/l, 18 percent of the iron is associated with organic matter. In Hamilton Harbour, average iron and TOC are about two-thirds of the above figures. At higher iron concentrations in natural water, Plumb and Lee found a greater association with organic matter. It would be interesting to look for complexed iron in waste samples, which frequently contain high TOC or COD values (Tables 4 and 5), using the method of Plumb and Lee (1973). They fractionated water samples on Sephadex gel filtration columns, and by studying iron recovery in the presence of a specific iron complexing agent (2, 4, 6 - tripyridal - s - triazine), showed that only complexed iron is passed through the column.

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TABLE 1

SOLUBILITY OF VARIOUS FORMS OF IRON

Figures are taken from Hutchinson, 1957, p. 705.
All figures are in μg. atom/l

	pH8	pH7	pH6
$a_{Fe^{3+}}$	$10^{-13.9}$	$10^{-10.9}$	$10^{-7.9}$
$a_{FeOH^{2+}}$	$10^{-8.3}$	$10^{-6.3}$	$10^{-4.3}$
$a_{Fe(OH)_4^-}$	$10^{-5.3}$	$10^{-6.3}$	$10^{-7.3}$
$a_{Fe^{2+}}$ at E=0.4v	$10^{-7.5}$	$10^{-4.5}$	$10^{-1.5}$
E=0.2v	$10^{-4.0}$	0.1	100
E=0.0v	0.3	300	3×10^5

Limit of analytical detectability is about 0.1 μg-atom/l.

TABLE 2

TYPICAL IRON ANALYSES FROM HAMILTON HARBOUR STATIONS LOCATED NEAR THE STEEL PLANTS (all values in mg/l)

Sampling Dates	Depth (m)	Station Numbers 262	259	256	20
Aug. 6-7	0.2	.45	.45	1.70	.80
	3.0	.55	.50	.70	1.00
	6.0	.55	.45	1.70	
	9.0		.50	.95	
	12.0		.35	1.00	
	15.0		.35		
Sept. 5-8	0.2	.40	.40	.65	.85
	3.0	.35	.40	.40	.85
	6.0	.40	.40	.55	
	9.0		.40	.48	
	12.0		.30	.42	
	15.0		.50	.40	
Oct. 4-5	0.2	.30	.25	1.25	3.7
	3.0	.35	.25	.25	1.1
	6.0	.25	.20	.20	
	9.0		.25	.20	
	12.0		.65	.75	
	15.0		.95		
Oct. 31- Nov. 1	0.2	.95	.50	2.3	2.0
	3.0	.70	.60	1.35	1.7
	6.0	.60	.55	.70	
	9.0		.45	.68	
	12.0		.45	.52	
	15.0		.40		
Mean (all of 1972)		0.52	0.46	1.0	1.3
Std. Dev. (all of 1972)		0.19	0.20	1.0	1.3

Note: Above data were selected from 1972 Hamilton Harbour survey data.

TABLE 3

TYPICAL PHOSPHATE ANALYSES FROM HAMILTON HARBOUR STATIONS LOCATED NEAR THE STEEL PLANTS (all values in mg/l as P)

Sampling Dates	Depth (m)	262 T	262 S	259 T	259 S	256 T	256 S	20 T	20 S
Aug. 6-7	0.2	.050	.015	.045	.015	.065	.048	.075	.009
	3.0	.045	.020	.040	.015	.042	.022	.090	.013
	6.0	.045	.020	.040	.020	.030	.018		
	9.0			.025	.020	.038	.018		
	12.0			.020	.020	.032	.012		
	15.0			.020	.015				
Sept. 5-8	0.2	.070	.015	.095	.015	.050	.015		
	3.0	.025	.012	.055	.015	.035	.010	.055	.015
	6.0	.055	.020	.037	.018	.042	.008		
	9.0			.045	.010	.017	.005		
	12.0			.030	.010	.010	.005		
	15.0			.040	.025	.010	.005		
Oct. 4-5	0.2	.050	.006	.045	.010	.042	.006	.320	.078
	3.0	.045	.008	.040	.010	.038	.009	.320	.210
	6.0	.050	.008	.050	.010	.035	.008		
	9.0			.045	.010	.040	.010		
	12.0			.035	.008	.032	.004		
	15.0			.025	.004				
Oct. 31 -Nov. 1	0.2	.048	.012	.060	.016	.076	.022	.300	.037
	3.0	.051	.010	.060	.015	.055	.016	.141	.030
	6.0	.052	.014	.062	.012	.083	.015		
	9.0			.056	.016	.073	.015		
	12.0			.058	.014	.069	.018		
	15.0			.056	.014				
Mean (all of 1972)		.064	.020	.042	.013	.065	.017	.21	.07
Std. Dev. (all of 1972)		.023	.017	.017	.005	.032	.008	.18	.09

Note: T=Total Phosphate
S=Soluble Phosphate
Above data were selected from 1972 Hamilton Harbour Survey data

TABLE 4

IRON AND ORGANIC CARBON DATA
STELCO AND DOFASCO OUTFALLS AND INTAKES

Location	Fe		TOC		Flow
	Mean	Std. Dev.	Mean	Std. Dev.	10 gal/day
Stelco:					
S. Open Cut Sewer	3.0	1.4	13	5	54.0
N. Trunk Sewer	5.0	4.1	15	8	54.6
148" Plate Mill Lagoon	9.8	6.9	16*	2	10.8
E. Side Lagoon	10.1	2.9	11	2	152.9
Hot Strip Finishing Mill	865.	7.	35	40	0.355
#3 Open Hearth Sewer	6.1	9.3	10	1	46.6
HCl Regen, 4 Stand Cold Mill	20.	16.	12	2	5.67
Heavy Gauge Shear Line	6.3	8.0	25	22	0.20
Service Water Intakes					
#2	0.54	0.20	8	3	292.5
#1	1.3	0.5	10	2	44.6
Dofasco:					
Ottawa St. Sewer	37.0	31.	25**	31	46.0
Coke Oven By-Products	2.6	2.1	13	2	28.8
Boilerhouse	2.5	1.0	9	3	30.0
Lagoon	3.9	1.7	9*	3	76.3
Silicon Steel Plant	0.29	0.06	9	4	0.87
Raw Water Intake	0.81	0.28	10	1	173.

Notes: All concentrations are in mg/l
Means and std. deviations are of 4 composite samples taken between May 1972 and January 1973
*-One questionably high value was omitted.
**-One questionably low value was omitted.

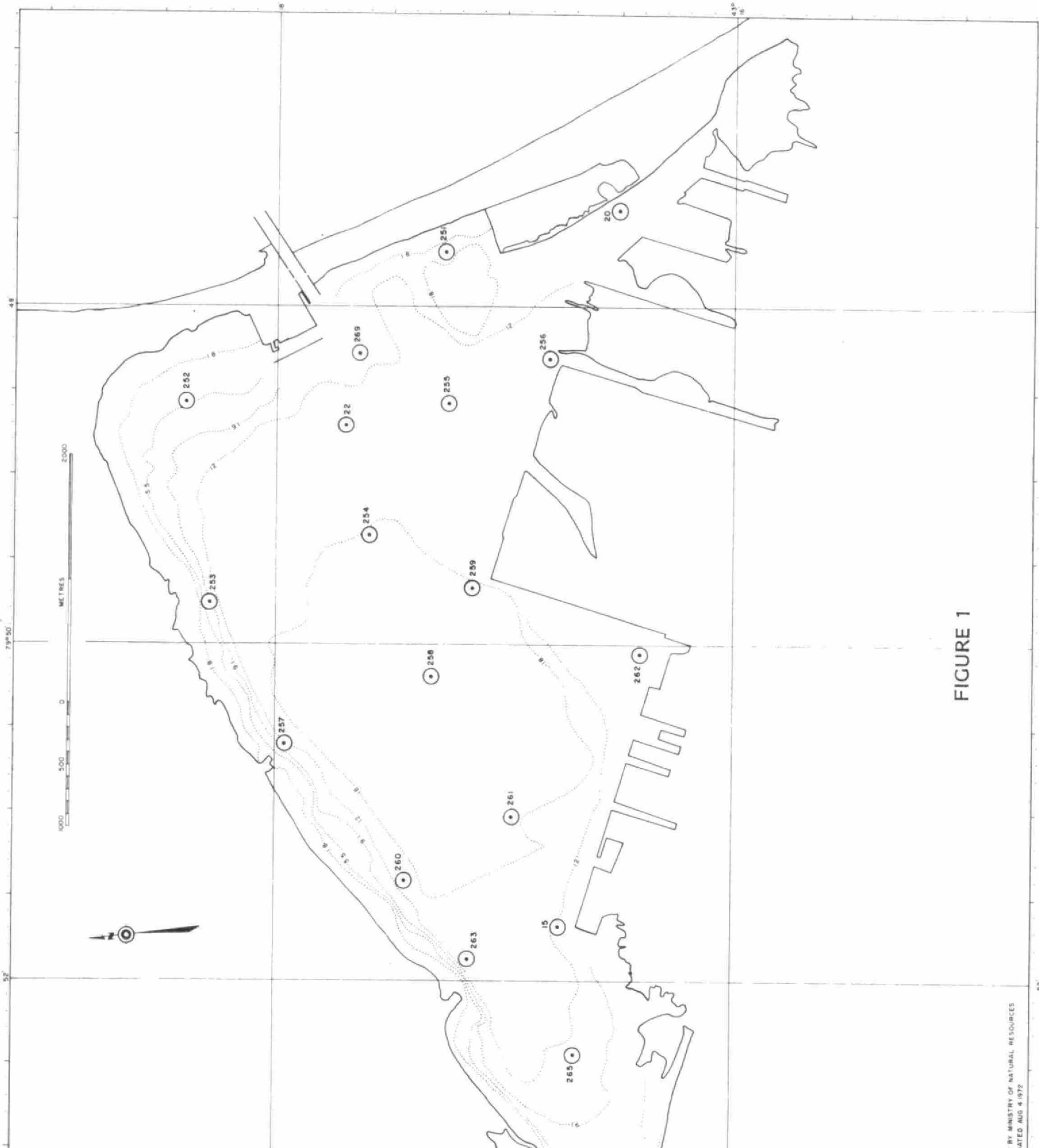
METRES
1000
500
0
2000
252
253
257
260
263
265
269
22
255
254
259
258
261
256
262
15
20
SHORELINE AS DEPICTED BY MINISTRY OF NATURAL RESOURCES
AERIAL PHOTOGRAPHS DATED AUG 4 1972

FIGURE 1

HAMILTON HARBOUR STUDY

section D

dissolved oxygen

HAMILTON HARBOUR STUDY

SECTION D

DISSOLVED OXYGEN

SUMMARY

DISSOLVED OXYGEN STOCKS IN HAMILTON HARBOUR HAVE BEEN CALCULATED BY NUMERICAL INTEGRATION OF DISSOLVED OXYGEN-DEPTH PROFILES FOR EACH SAMPLING LOCATION. WEIGHTED MEAN DISSOLVED OXYGEN-DEPTH PROFILES WERE USED BECAUSE THE 1972 DATA WERE NOT SYNOPTIC, AND BECAUSE DEPTH DISTRIBUTION DATA WERE VERY LIMITED FOR YEARS BEFORE 1972.

ALTHOUGH DISSOLVED OXYGEN STOCKS WERE SOMEWHAT HIGHER IN 1972 THAN IN 1966-70, THE HARBOUR IS STILL LESS THAN 50 PERCENT SATURATED IN AUGUST. INCREASED WATER LEVELS AND WIND SPEEDS IN 1972 HAVE CONTRIBUTED TO THE INCREASED DISSOLVED OXYGEN STOCK. THE DEPTH-TIME DISTRIBUTIONS FOR DISSOLVED OXYGEN IN 1972 ARE CONSISTENT WITH THE EFFECTS OF WIND MIXING, PHOTOSYNTHESIS AND SEDIMENT DEMAND. LARGE AREAS NEAR THE BOTTOM HAVE DISSOLVED OXYGEN VALUES BELOW THE FISH, AQUATIC LIFE AND WILDLIFE CRITERION OF 5 MG/L, AND IN SOME CASES ARE ANOXIC, REFLECTING SEDIMENT OXYGEN DEMANDS.

AS WASTE LOADINGS ARE ESTIMATED TO REPRESENT ONLY ABOUT 6 TO 7 PERCENT OF THE TOTAL OXYGEN DEFICIT IN AUGUST, REDUCTION OF CHEMICAL OXYGEN DEMAND LOADINGS SHOULD BE INITIATED AS SOON AS POSSIBLE AS IT WILL TAKE SOME YEARS TO BE EFFECTIVE IN ELEVATING DISSOLVED OXYGEN LEVELS. IT IS ALSO IMPORTANT THAT SOME STEPS BE TAKEN TO REDUCE PHYTOPLANKTON GROWTH AND OXIDIZE SEDIMENTS.

HAMILTON HARBOUR STUDY

DISSOLVED OXYGEN

As part of the Hamilton Harbour study, an analysis of the dissolved oxygen stock in Hamilton Harbour and its trends since 1966 has been performed. In 1966, 1969 and 1970, the Hamilton municipal laboratories conducted a 7 station survey of surface dissolved oxygen values, supplemented by limited depth profiles. The eight station grid used by the Ministry of the Environment in 1972 was similar to the municipal laboratory network with the exception of Station 252. In 1971, a weekly analysis of dissolved oxygen stock was performed by the Hamilton municipal laboratories from June to August (Matheson, 1972). This analysis involved the collection of samples from various depths at 20 sampling stations; the grand mean of all DO values obtained was multipled by the harbour volume to obtain the total stock.

In 1972, DO data were obtained as a part of the intensive Hamilton Harbour survey program. Depth profiles were obtained at every station at 1.5 m depth increments from the surface to 6 m, and at 3 m increments below 6 m. The eight station grid was surveyed on March 29, April 28, and approximately weekly from mid-July to mid-November. This was supplemented by a survey of 18 sampling stations, performed on 4 dates from August to November. Figure 1 indicates the location of the sampling stations used.

As it is desirable that Hamilton Harbour support a diverse aquatic community following implementation of loading reductions, minimum hypolimnetic dissolved oxygen values have been compared to the minimum criterion for protection of fish, other aquatic life and wildlife (warm-water biota) (MOE, 1972) of 5 mg/l.

Method of Calculation

The harbour was subdivided into eight regions corresponding to the eight station sampling grid, by drawing the right bisectors of the lines joining the stations. The regions obtained are shown in Figure 1. A similar set of sub-regions corresponding to the 17 station sampling grid was also calculated. Areas and volumes of the sub-regions were calculated using depth contours obtained from a Canadian Hydrographic Service chart. Depths were corrected according to monthly mean water level data (NOAA, 1969-71; Canadian Hydrographic Service, 1970). The total surface area thus obtained was 20.9×10^6 m^3, and the total volumes in July 1972 computed from the 17 station and 8 station configurations were 279×10^6 m^3 and 270×10^6 m^3, respectively. The latter data are in good agreement with a figure obtained by Canada Centre for Inland Waters in 1969, 287×10^6 m^3.

Initially, three methods were used in calculating dissolved oxygen stock.

1. Each region was subdivided into epilimnion and hypolimnion, and

region DO stocks were calculated from the mean DO analysis in each layer. The region DO stocks were summed for the total stock.

2. The overall average DO value for each station was used to calculate a mean value for each region and summed for the total stock.

3. The grand mean of all DO values was multiplied by the total harbour volume for the total stock.

Although the results obtained by methods 2 and 3 were identical within experimental precision of DO measurement ($\pm 5\%$) the result obtained by method 1 was about 20% lower than that obtained by the other methods. This difference was attributed to the larger number of samples obtained in the epilimnion compared to the larger volume hypolimnion. On the average, about 4 samples were obtained from the epilimnion and 3 from the hypolimnion.

However, method 1 was judged to be unsuitable for computation of DO stocks from previous years, for two reasons: (a) Depth distribution data are very limited for years before 1972, and (b) the data were not synoptic and internal waves were present. Consequently, the position of the thermocline varied greatly from one station to another, a situation which is physically impossible.

Therefore, harbour wide average DO-depth profiles were used as follows. A monthly mean dissolved oxygen as a fraction of the surface value was computed for each depth on a harbour wide basis for 4 sampling surveys in August and 4 surveys in September. Using the observed surface DO results, a DO-depth profile was calculated for each station. A DO stock per unit area was calculated for each station by numerical integration of this profile from the surface to the average sounding of the individual station. This was multiplied by the subregion area to give the DO stock for the region, which was then summed over the entire bay. For each sampling date, DO stocks were also calculated from the actual DO-depth profiles.

In Table 2, DO stocks calculated from the monthly mean DO-depth profiles are compared to those calculated from individually measured profiles for August 1972. Although differences greater than 25% are found for individual surveys, the monthly mean DO stocks (Table 7) calculated by the two methods are within 6% of each other, an error similar to the experimental error in DO measurement.

For a single date (July 21), the result obtained using observed DO-depth profiles (1.27×10^6kg) was in good agreement to that obtained using method 1 described above (1.22×10^6kg).

Results of DO stock calculations for 1972 using this method are presented in Tables 1-4.

Comparison of Observed and Calculated Depth Profile

Some depth data were obtained in August and September 1966 for station 258. These data are compared to 1972 monthly mean data in Table 5. The calculated results for 1966 are slightly lower than those for 1972, reflecting the tendency to higher surface DO values in 1972. Spatial and temporal variations in the position of the thermocline are reflected in the DO at 6m in August for both years.

The original calculation of DO-depth profiles for August data used only data for the 17 station survey on August 6-7. As surface values tended to be higher on that date than at other times in the month (reflected in the higher stock indicated in Table 2), a large discrepancy in the 1966 depth profiles was obtained. This difficulty was resolved by using data from other August 1972 sampling dates. The difference between the DO stock calculated using 1972 average profiles (0.87×10^6kg) and that calculated from 1966 average profiles (1.04×10^6kg) is satisfactory considering the gross nature of the assumptions used in these calculations. Both the 1966 and 1972 average profiles are not based on synoptic data due to internal wave and seiche activity. Similarly harbour water volumes are determined from one water level recorder and hydrographic charts.

Several dissolved oxygen-depth profiles obtained in September 1970 are compared to calculated profiles on the basis of September 1972 average profiles in Table 6. A higher depletion rate with depth at station 20 and 257 was observed in 1970. This may be indicative of reduced oxygen demand from sediments derived from the Hamilton WPCP in 1972, or it may be due to greater re-aeration of the surface water in 1972 (average wind speeds in September were 2.9 and 4.3 m/sec in 1970 and 1972). The effect of sewage oxygen demand is indicated by the low surface DO values and greater depletion rate with respect to depth at this station compared to the rest of the harbour.

On the other hand, station 269 experienced no depletion in 1970. This could have been simply due to a strong inflow of oxygenated lake water when these samples were obtained; this effect may also have influenced the result for station 258 on the same date. The remaining profiles were similar in the two years. The average values of DO (depth)/DO (surface) in 1970 were slightly higher than 1972, particularly at 1.5 and 3 m. Although this appears to indicate greater photosynthetic oxygen production in 1970, chlorophyll a data do not support this hypothesis. (Average chlorophyll a concentration was 12 ug/l in September 1970 and 21 ug/l in 1972). On account of this difference, the 1970 average figures were also used to calculate DO stocks, and the results are given in Table 8.

Comparison of DO Stock: August 1966-72 and September 1966-72

Results of DO stock calculations by the above methods are given in Table 7 for August and Table 8 for September. The DO stock appears to be significantly higher in 1972 than in 1966-70, while the difference between the earlier years is insignificant, considering the the magnitude of the spread between calculations based on different depth profiles. In considering the significance of the higher DO stock in 1972, the following facts must be noted: (1) The difference is much less than the observed seasonal differences in DO stock observed in 1972. (The DO stock on April 28, 2.7×10^6kg, is double the August figure.) (2) The higher DO in 1972 resulted from the combined effects of higher surface DO values and higher water levels. The August 1972 average water level was 0.4 m (1.4 ft) above the August 1966 level. If the DO were expressed as a fraction of saturation DO stock, a greater saturation deficit may well have occurred in 1972. (3) The average wind speed in Hamilton (Department of Transport, 1966, 1969, 1970, 1972) was 3.6 m/sec in August 1972 compared to 3.1, 3.0 and 2.8 m/sec in August 1966, 1969 and 1970 respectively. Therefore, the surface waters were more thoroughly aerated.

Comparing the difference between surface and hypolimnetic DO in 1966 and 1972, it is apparent that the sediments in 1972 are exerting as much as, if not greater oxygen demand, than in 1966.

Dissolved Oxygen Curve - 1972

The curve of DO stock vs. date is plotted in Figure 2. Due to the lack of sampling in May and June, the slope of the descending portion in unknown. In order to test the effect of temperature on producing the observed decrease in DO stock, saturation DO stocks were calculated for March 29, April 28 and July 21. The results (Table 1) indicate that the harbour was 76, 83 and 43 percent saturated with DO on the above dates. The effect of oxygen demand is thus low in April, but in May to July, the effect of temperature is low compared to that of oxygen demand in determining total stock. The stock was relatively constant from mid-July to mid-September, after which it increased to a maximum of 2.06×10^6kg on September 25. The sharp increase between September 13 and 19 correlated with a period of increased wind aeration. (Average wind speed for September 14-19 was 5.1 m/sec while average for August 1- September 13 was 3.6 m/sec). The increase between October 10 and 18 occurred during a period of high winds (average 6.1 m/sec) and decreasing air temperature (daily average dropped from 10^{o}C to 0^{o}C between October 11 and 18). Water temperature also decreased by 3^{o}C in this period. Winds were generally lighter during intervals of decreasing DO content, except for the first half of the September 25-October 5 interval. However, the latter part of this interval was characterized by warm sunny weather, consistent with maintaining stratification. Thus, the form of the DO curve in the late summer and fall of 1972 is reasonably consistent with meteorological expectations.

Depth-time distributions for dissolved oxygen are plotted in Figures 16 and 17 for Stations 265 (9 m depth, s.w. corner of bay) and 258 (21 m depth, center of bay) respectively. Dissolved oxygen isopleths for Station 265 illustrate the effects of wind mixing, photosynthesis and sediment demand. Supersaturated conditions were created at the surface on August 7 and 21, and September 25, roughly coinciding with times of high algae growth, as indicated by chlorophyll a data. (Chlorophyll a values were 19, 22 and 28 ug/1 on the above dates, contrasted with intermediate minimum values of 14 and 18 ug/l). The decreased hypolimnetic DO values indicate the presence of sediment demand. Also mixing due to increased wind speeds (5-6 m/sec) which occurred prior to sampling on August 14 and 29, and September 20 are evident. On the latter date, complete mixing through the water column occurred at this station.

Similar, through less obvious effects occurred at Station 258. Although supersaturated conditions did occur near the surface on several dates, no readily identifiable correlation with chlorophyll a was observed. Due to the greater depth of water at this station, the bottom DO remained below 2 mg/l until after October 10, although mixing before September 20 produced aeration of the water to a depth below 12 m. Complete mixing (overturn) was produced by high winds and decreased air temperatures between October 10 and 18. These mixing periods correspond to the time of increased DO stock in the entire bay, as mentioned above (Figure 2).

Depth-time distributions have also been plotted for alkalinity (Figures 18 and 19). As wind-induced circulation should remove dissolved CO_2 to the air, the alkalinity should decrease as the following reaction proceeds to the right:

$$H^+ + HCO_3 \rightleftarrows H_20 + CO_2$$

Photosynthetic removal of CO_2 should also cause this reaction to go to the right, but oxidation of organic matter and respiration will cause it to go to the left. It is a combination of these processes which causes the familiar diurnal pH and dissolved oxygen cycle.

At both Stations 258 and 265, the alkalinity drops between August 6 and 14 as expected due to the wind-induced circulation. Some decrease in alkalinity occurred between September 14 and 20 at Station 265, but not at Station 258, although the pH increased by an average of about 0.3 unit at Station 258, as expected from the above reaction. A definite decrease in alkalinity, especially near the bottom, occurred before October 18 at Station 258, when complete overturn occurred.

Although some tendency for the alkalinity to increase as a result of oxidation of organic matter was seen, the photosynthetic effect was not visible. The diurnal dependency of these parameters, coupled with the lack of synoptic measurements (sampling surveys took many hours to two days to perform for 8 stations, two to four days for 17 stations) makes a detailed analysis of the seasonal changes of alkalinity and pH impossible.

Local Areas of Greatest Dissolved Oxygen Depletion in 1972

Integrated dissolved oxygen profiles at each station were also used to estimate the extent of DO depletion at each sampling station. These were calculated as described earlier, except that an average DO-depth profile was used for each individual date, in order to remove short term effects on the thermocline position such as internal waves and their reflections. Integrated profiles thus calculated are given in Table 9. Monthly averages of these profiles were divided by the spring average profile to give the fraction of the spring DO present at each station.

Results of this calculation, along with the locations of greatest DO depletion in each month, are given in Table 10. Overall, the greatest problem area is at Station 256 (Ottawa St. slip). Station 255 (west end of bay) also presented a serious depletion problem in July. Depletion in the vicinity of the Hamilton sewage treatment plant was much more serious in October than at other dates; in July and August, the extent of depletion calculated by this method was surprisingly small. This unexpected result is an artifact of the conditions existing at Station 20, for the following reasons: (a) The shallowness of the water at this station (about 6.5 m) places the entire profile within the epilimnion, and subject to reaeration by wind and wave action. The observed temperature difference between surface and 6 m is generally less than 2°C. (b) The nutrient discharge allowed a high level of photosynthesis of oxygen in July (chlorophyll a readings were 46.7 and 56.9 ug/l on July 21 and 25, respectively). Later decomposition of dead plankton resulted in low DO levels in September and October. (c) Oxygen demand as a result of sewage causes considerable DO depletion even in early spring (DO=6.3 mg/l at 9.5°C or 55% saturation at Station 20 on March 29). If the data were expressed as a saturation deficit, a considerably greater depletion would be seen for this station compared to other stations, especially those located away from the greatest industrial discharges. Using this method, the worst depletions would occur at Stations 20, 256 and 265, in order of decreasing severity.

In Table 11, the lowest DO values obtained for each station during every survey from July to October are given. In most cases, these values were obtained at or near the bottom. Areas in which the minimum hypolimnetic DO is less than the fish, aquatic life and wildlife criterion of 5.0 mg/l (shown in Figures 3-14 by shading) cover nearly the entire bay until mid-September, and are fairly widespread until early October. The area of greatest concern (DO below 0.5 mg/l) extends mainly from the vicinity of Stelco (Stations 256 and 259) to the deepest points in the bay (Stations 258 and 261). In this region, sufficient oxygen demand was exerted by the sediments to allow reducing conditions to occur from early August to mid-September.

In the sampling surveys of August 6 and 14, September 6 and 13, and November 1, the area of DO < 5 mg/l included Stations 269, and consequently the Burlington ship canal. Although this may seem surprising, because of the tendency for higher DO lake water to be present, very low DO levels (< 2 mg/l) were observed at the recording chemistry meter location 3.6 m from the bottom of the ship canal

in August 1973 for 3 days. A portion of this record is included in Figure 15. Additional details of the DO values observed in the ship canal are included in Section "A", Harbour Periodicities.

Suggestions for Improvement of Dissolved Oxygen Levels

While it is recognized that hypolimnetic dissolved oxygen levels may naturally drop below the fish, aquatic life and wildlife criterion of 5 mg/l, chemical oxygen demand (COD) loadings from the industries are obviously important in producing the very low observed DO levels. The 1972 mean hypolimnetic DO concentration over the entire bay was 4.2 mg/l, contrasted to Lake Ontario mean hypolimnetic values of 11.5-13 mg/l, observed in 1967 (Sweers, 1969). Average values for the major COD loadings to Hamilton Harbour are indicated in Table 12. While no treatment exists for oxygen demand some removal is affected by other waste treatment. If conventional treatment were incorporated, a reduction in COD loading by about 33 percent could be expected. With improved treatment, a reduction of COD loading by approximately 66 percent can be obtained, as has been recommended (Section E, Numercial Model). It is obviously important to determine whether this reduction would be sufficient to elevate the low DO levels.

Figure 2 represents a partial plot of the 1972 record of the dissolved oxygen stock in Hamilton Harbour. As discussed previously, this plot is a mean value integrating both area and depth measurements in the harbour. It represents the sum of both oxygen depletion and addition processes. The rates of the components of these processes are obviously variable and no measure of these rates were undertaken in this study. However, it is possible to make some estimates from Figure 2. If one assumes that the oxygen demand in April (computed from observed and saturation DO stocks, Table 1) is mainly due to waste discharges and bottom sediments, approximately 0.7×10^6 kg of stock are utilized for this purpose. In August, the demand is approximately 1.5×10^6 kg of stock which includes oxygen demand due to seasonal phytoplankton decay assuming equilibrium. By use of the temperature coefficient $(1.046)^{\Delta t}$, where Δt is the difference between the average bottom temperatures in August (all stations, 5 surveys) and April 28, it is estimated that about 1.0×10^6 kg of stock are used by waste discharges and bottom sediments. Thus discharges and bottom sediments represent approximately two-thirds of the deficit during the critical period in August. It must be recognized that this is only a rough estimate, as bottom temperatures in August 1972 varied by more than 10°C with space and time.

Daily BOD and COD loadings to the harbour (Table 12) are approximately 1.0×10^5 kg. If one assumes that periodic variations of DO have periods less than a day an equilibrium exists between depletion and addition processes over a 24 hour period. Waste loadings are then of the order of 6 to 7 percent of the deficit so that conventional treatment would reduce the deficit 2 percent in the critical period. The percentage reduction is dependent on the period selected for equilibrium, e.g. if it is 48 hours treatment reduces the deficit by 4 percent. However, it is likely that an equilibrium period lies somewhere between 18 and 96 hours, which means a reduction in deficit between 1.5 and 8 percent in August.

In succeeding years, the extent of reduction will probably be less. The amount of reduction achieved will be a function of accumulating sediment demand, trophic levels, dissolved oxygen concentration gradients at the mud interface, and meteorological conditions which control atmospheric reaeration rates and mixing of the stratified water column. An optimistic estimate is that reductions in nutrient discharge would change the trophic state so that less phytoplankton accumulates in the sediments than is oxidyzed each year. Ultimately the oxygen demand of the sediments would be satisfied, and the DO deficit would only be a function of COD demands. If the average total phosphorus concentration were reduced to 40 ug/l P, the chlorophyll a concentration would be reduced by approximately 50 percent (Brydges, 1971). Assuming that the reduction in chlorophyll a concentration will produce a similar reduction in sediment demand due to decaying phytoplankton, the reduction in sediment oxygen demand due to decreased nutrient input would be comparable to the recommended COD loading reduction. Until COD demands become limiting, a roughly experimental reduction in deficit might be expected to occur. Under this assumption, a decrease of 2 percent per year would result in a 1/3 decrease in oxygen deficit after 20 years. However, this is only a rough estimate of a decrease rate, based on observed seasonal deficits and estimated periodic variations. But it does indicate that many years could be required before a large reduction in oxygen deficit takes place.

On the other hand, if nutrient removal does not appreciably affect the trophic state and phytoplankton accumulates in the bottom sediments, the reductions in deficit in successive years will be much less until increased bottom sediment demand balances the achieved reductions in COD demand, with only a very minor decrease in DO deficit having be achieved. This represents a very undesirable environmental situation, as the water quality could then degrade as a result of increased sediment demand, or at best move towards either slight improvement or degradation depending upon long term meteorological conditions.

A 1/3 decrease in oxygen deficit in August would correspond to an increase in August DO stock from the 1972 average value of 1.3×10^6kg to about 1.8×10^6kg, a figure comparable to conditions in mid-October, 1972. By comparison with Figures 11-13, it would be expected that bottom water in the relatively shallow north and northwestern portions of the bay would have more than 5 mg/l; however, close to the municipal and industrial outfalls, more severe depletion would still be noticed. The area affected by low DO levels would undoubtedly be affected by meteorological conditions, as has been indicated by the 1972 results.

Conclusions

Dissolved oxygen stocks in Hamilton Harbour have been calculated from measured DO data for 1966-72. Weighted monthly mean DO-depth profiles for August and September 1972 have been used to estimate DO-depth distributions for previous years when depth data were not obtained. From 1966 to 1972, the August DO stock increased from 1.0 to 1.4 x 10^6kg; in the same period, the mean September DO stock increased from 1.1 to 1.7 x 10^6kg. Although a significant increase in DO stock has apparently occurred, the harbour is still less than 50 percent saturated in August. Increased water levels and wind speeds in 1972 have also contributed to this observed increase in DO stock.

Large areas near the bottom still have DO values below the fish, aquatic life and wildlife criterion of 5 mg/l. Indeed, DO values below 0.5 mg/l were reported from August to September in the region of the bay extending from the vicinity of Stelco to the deepest areas. These low DO values reflect the oxygen demand of bottom sediments. As waste loadings are estimated to represent only about 6 to 7 percent of the total oxygen deficit in August, reduction of COD loadings should be initiated as soon as possible as this will require some years to be effective in elevating DO stock. Nutrient removal is also required, in order to decrease the oxygen demand from decomposing phytoplankton and accumulating bottom sediments. Some oxidation of bottom sediments, as well as reaeration of low DO hypolimnetic waters by mixing with surface water, will result if artificial destratification is undertaken.

Due to the general lack of depth data from previous years, it is impossible to state whether or not DO depletion within the hypolimnion is becoming more severe with time. However, the detailed information in 1972 will serve as a background for interpreting future trends in DO in Hamilton Harbour.

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TABLE 1

Dissolved Oxygen Stock

Spring and July, 1972

All Figures are in 10^3 Kg

	Station									
Date	20	252	256	257	258	262	265	269	Total	Saturation
Mar 29	63	---	251	455*	897	228	464	603*	2961	3879
Apr 28	108	---	270	443*	883	224	479	531*	2938	3523
July 21	70	102	103	144	300	106	151	296	1272	2932
July 25	77	146	55	93	412	167	81	388	1418	

Note: All data taken from MOE Hamilton Harbour Surveys, and calculated from actual DO-depth profiles.

*Include portion of area for station 252, which was not sampled on March 29 and April 28.

Saturation stocks were calculated from temperature data and oxygen solubility tables.

TABLE 2

Dissolved Oxygen Stock

August 1972

All Figures are in 10^3 Kg.

Date		Station 20	252	256	257	258	262	265	269	Total
Aug 1	(a)	64	162	59	120	306	119	121	380	1331
	(b)	67	50	36	177	329	133	212	223	1227
Aug 6-7										
	(a)	73	153	94	180	496	103	214	180	1493
	(b)	80	228	73	295	372	145	329	330	1852
										1536*
Aug 14										
	(a)	53	133	100	184	360	112	232	251	1425
	(b)	50	114	73	121	198	133	185	178	1052
Aug 29										
	(a)	38	131	114	174	318	89	235	221	1320
	(b)	47	117	64	153	273	75	212	143	1084

Notes: All data taken from MOE Hamilton Harbour Survey

(a) Calculated from actual DO-depth profile

(b) Calculated from weighted mean DO-depth profile for entire month.

* Calculated from actual profiles using 17 station grid

TABLE 3

Dissolved Oxygen Stock

September 1972

All Figures are in 10^3 Kg.

Date		Station 20	252	256	257	258	262	265	269	Total
Sept. 5-8										
	(a)	72	154	126	186	291	90	227	230	1377
	(b)	75	168	139	174	334	87	275	212	1464
										1272*
Sept. 13-14										
	(a)	29	148	145	192	310	138	180	184	1326
	(b)	29	92	128	186	334	116	227	181	1293
Sept. 19-20										
	(a)	23	143	138	302	512	134	378	283	1913
	(b)	46	142	132	208	355	117	282	287	1569
Sept. 25										
	(a)	61	188	218	227	445	143	355	418	2056
	(b)	63	186	170	232	401	114	358	299	1823

Notes: All data taken from MOE Hamilton Harbour Survey

(a) Calculated from actual DO-depth profile

(b) Calculated from weighted mean DO-depth profile from entire month.

* Calculated from actual profiles using 17 station grid

TABLE 4

Dissolved Oxygen Stock

October-November, 1972

All Figures are in 10^3 Kg.

Date	Station 20	252	256	257	258	262	265	269	Total
Oct 4-5	17	151	157	280	424	148	383	301	1861 1769*
Oct 10	23	154	182	235	402	147	290	303	1737
Oct 18	49	152	183	244	580	139	299	327	1973
Oct 24	7	122	136	208	466	141	260	268	1609
Oct 31-Nov 1	21	103	117	198	471	102	262	234	1507 1383*
Nov 9	40	139	152	222	500	128	268	240	1689
Nov 15	56	133	167	249	583	146	309	285	1928

Note: *Total DO stock calculated using 17 station grid.

TABLE 5

Dissolved Oxygen Profiles

At Station 258

August 1966 and 1972

Depth (m)	1966 (mg/l) Av. Observed	Calculated	1972 (mg/l) Av. Observed	Calculated
0.2	6.4	6.4	9.5	9.5
1.5	---	---	9.6	8.7
3.0	6.0	5.4	8.5	8.0
4.5	---	---	7.8	7.0
6.0	4.9	3.1	7.6	4.7
9.0	2.5	1.9	2.2	2.9
12	1.6	1.0	1.1	1.5
15	1.1	0.3	2.1	0.5
18	0.8	0.8	2.1	1.3

September 1966 and 1972

Depth (m)	1966 (mg/l) Observed	Calculated	1972 (mg/l) Av. Observed	Calculated
0.2	5.7	5.7	8.5	8.5
1.5	---	---	8.3	8.2
3.0	5.2	5.3	8.3	7.9
4.5	---	---	8.0	7.8
6.0	4.8	5.0	8.1	7.5
9.0	4.6	2.9	4.9	4.4
12	2.1	1.8	3.3	2.7
15	1.9	0.9	1.2	1.4
18	0.5	0.5	1.0	0.8

Calculated depth profiles are based on observed surface DO values and 1972 monthly average DO-depth profiles.

TABLE 6

Dissolved Oxygen Profiles in September 1970 and 1972

(a) 1970

Depth (m)	20 Obs	20 Calc	257 Obs	257 Calc	258 Obs	258 Calc	265 Obs	265 Calc	269 Obs	269 Calc
0.2	3.0	3.0	8.6	8.6	6.6	6.6	7.0	7.0	5.0	5.0
1.5	3.5	2.9	7.5	8.3	7.3	6.4	6.9	6.8	6.0	4.8
3.0	2.6	2.7	7.6	8.0	7.4	6.2	6.8	6.5	7.2	4.7
4.5	0.4	2.8	6.6	7.9	7.5	6.0	6.4	6.4	7.4	4.6
6.0	0.4	2.6			6.9	5.8	6.0	6.1	7.2	4.4
9	0.4	1.6			6.1	3.4	3.4	3.6	6.8	2.6
12					3.4	2.1	3.2	2.2		

(b) 1972

Depth (m)	20 Obs	20 Calc	257 Obs	257 Calc	258 Obs	258 Calc	265 Obs	265 Calc	269 Obs	269 Calc
0.2	5.5	5.5	8.3	8.3	8.5	8.5	8.3	8.3	7.9	7.9
1.5	5.6	5.3	8.2	8.0	8.3	8.2	8.2	8.0	7.9	7.7
3.0	4.2	5.1	7.9	7.7	8.3	7.9	8.1	7.7	7.6	7.4
4.5	2.4	5.1	7.8	7.6	8.0	7.8	7.6	7.6	7.3	7.3
6.0			7.9	7.2	8.1	7.5	6.5	7.2	6.8	6.9
9			5.4	4.3	4.9	4.4	4.5	4.3	5.3	4.1
12			4.3	2.6	3.3	2.7	2.8	2.6	2.0	2.5
15					1.2	1.4				
18					1.0	0.8				

Note : All values are in mg/l

Calculated depth profiles are based on observed surface DO values and 1972 monthly average DO-depth profiles.

TABLE 7

Dissolved Oxygen Stock

August Data, 1966 to 1972

All Figures are in 10^3 Kg.

	Station									
	20	252	256	257	258	262	265	269	Total	Number of Sampling Surveys
1966	29	---	53	144	198	59	164	223	870	6
1966*	31	---	63	174	245	70	190	267	1040	6
1969	53	---	75	157	303	101	201	313	1203	1
1970	47	---	68	166	249	74	189	284	1077	3
1972	61	127	62	186**	293	122	234	219**	1304	4
1972***	57	145	92	164**	370	106	200	229**	1392	4

Notes: Data for 1966-70 taken from Hamilton Municipal Laboratories annual reports.
Data for 1972 taken from MOE Hamilton Harbour surveys.
Unless otherwise indicated, data calculated from surface values at each station and August 1972 weighted mean DO-depth profile.
*Calculated from average DO-depth profile taken in August 1966 at station 256.
**Not comparable to previous years because of area attributed to station 252.
***Calculated from observed DO-depth profiles for each date.

TABLE 8

Dissolved Oxygen Stock

September Data, 1966 to 1972

All Figures are in 10^3 Kg.

	Station									
	20	252	256	257	258	262	265	269	Total	Number of Sampling Surveys
1966	33	---	73	178	263	73	214	305	1139	2
1969	33	---	108	268	349	76	277	377	1488	2
1970	20	---	62	228	286	75	268	237	1150	2
1970*	20	---	71	264	324	84	297	271	1330	2
1972	53	147	142	200**	356	108	286	245**	1537	4
1972***	46	158	157	227**	389	126	285	278**	1668	4

Notes: Data for 1966 to 1970 taken from Hamilton Municipal Laboratories annual reports.
Data for 1972 taken from MOE Hamilton Harbour surveys.
Unless otherwise indicated, data calculated from surface values at each station and September 1972 weighted mean DO-depth profile.
*Calculated from average DO-depth profile taken in September 1970 at stations 20, 257, 258, 265 and 269. As the maximum depth sampled in this month was 12 m, 1972 DO(depth)/DO (surface) figures were used for greater depths.
**Not comparable to previous years because of area attributed to station 252.
***Calculated from observed DO-depth profile.

TABLE 9

DO Stock Per Unit Area, 1972. (g/m^2)

Date	20	252	256	257	258	262	265	269
				Station				
Mar 29	39.7	---	126.6	151.5	224.2	129.6	119.6	126.6
Apr 28	68.7	---	136.4	147.5	220.7	127.5	123.4	111.4
July 21	43.4	65.1	43.6	55.3	84.3	63.0	37.7	87.3
July 25	48.2	88.4	24.3	79.7	98.7	75.4	31.6	100.6
Aug 1	39.4	63.5	18.0	74.3	99.6	71.7	47.8	73.6
Aug 6-7	46.4	86.1	30.0	100.0	78.0	68.4	71.4	85.3
Aug 14	34.6	60.1	44.8	62.9	71.5	90.5	55.4	72.5
Aug 29	32.5	68.3	39.7	76.8	81.7	52.9	71.9	55.9
Sept 5-8	47.8	71.9	63.0	63.5	73.2	44.9	65.0	60.3
Sept 13-14	18.9	56.1	60.9	71.4	75.5	62.1	54.8	54.1
Sept 19-20	28.6	71.2	80.3	105.3	116.6	77.9	81.5	114.0
Sept 25	40.3	92.8	95.8	106.7	114.3	71.9	102.5	107.7
Oct 4-5	12.2	81.5	76.7	112.5	110.6	71.3	101.3	93.4
Oct 10	14.3	69.5	87.9	102.6	101.1	82.8	80.4	110.6
Oct 18	32.9	72.3	72.8	102.4	146.0	90.8	85.8	116.2
Oct 24	3.9	58.2	71.9	89.4	118.5	70.6	69.1	85.1
Oct 31	9.0	37.7	65.2	84.4	116.0	57.3	67.1	77.2
Nov 9	26.6	61.9	75.2	99.0	126.9	75.7	74.5	78.4
Nov 15	37.0	65.5	73.8	104.1	152.3	91.7	86.3	87.7
Date of lowest DO Stock	Oct 24	Oct 31	Aug 1	July 21	Aug 14	Sept 7	July 25	Sept 13

Note: Above figures were calculated using average DO-depth profiles integrated over the bay for each individual date. Mar 29 and Apr 28 figures were calculated from observed profiles.

TABLE 10

DO Depletion, 1972

Month	Station 20	256	257	258	262	265	269
July	0.85	0.26	0.45	0.41	0.54	0.29	0.79
August	0.71	0.25	0.53	0.37	0.55	0.51	0.60
September	0.63	0.57	0.58	0.43	0.50	0.63	0.71
October	0.27	0.57	0.66	0.53	0.58	0.66	0.81
November	0.59	0.57	0.68	0.63	0.65	0.66	0.70

Note: Above data are values of the ratio DO (month)/DO (spring), where DO (month) is the average DO stock per unit area for the stated month and DO (spring) is the average of March 29 and April 28 values. Data used in calculating above figures were taken from Table 9.

Location of Greatest Depletion

July	256, 265
August	256
September	258
October	20
November	256

TABLE 11

Lowest Dissolved Oxygen Values Obtained on Each Date in 1972 (mg/l)

Station	July 21	July 25	Aug 1	Aug 6-7	Aug 14	Aug 29	Sept 5-8	Sept 13-14	Sept 19-20	Sept 25	Oct 4-5	Oct 10	Oct 18	Oct 24	Oct 31
15	---	---	---	0.2	---	---	1.6	---	---	---	8.4	---	---	---	5.5
20	10.0	6.8	7.0	8.0	5.0	2.4	7.0	2.4	1.2	6.0	1.2	2.1	4.0	0.6	1.4
251	---	---	---	5.1	---	---	0.5	---	---	---	1.0	---	---	---	4.0
252	1.0	4.4	8.3	8.7	7.0	6.0	7.5	6.7	6.3	7.9	6.9	6.9	7.0	5.5	4.1
253	---	---	---	0.8	---	---	7.0	---	---	---	8.0	---	---	---	5.0
254	---	---	---	0.8	---	---	1.6	---	---	---	1.8	---	---	---	5.2
255	---	---	---	0.4	---	---	2.0	---	---	---	5.7	---	---	---	5.2
256	1.8	1.0	0.1	0.1	0.0	1.2	1.6	2.2	1.8	3.8	4.4	6.7	5.5	5.0	4.1
257	2.1	1.0	1.0	1.0	4.0	5.6	3.2	1.2	8.0	5.6	6.7	6.3	6.2	5.8	5.3
258	1.8	3.8	0.2	0.5	0.0	0.0	0.4	0.4	1.8	1.0	1.4	0.4	6.8	5.2	5.2
259	---	---	---	0.7	---	---	0.3	---	---	---	0.5	---	---	---	5.0
260	---	---	---	0.8	---	---	0.8	---	---	---	1.2	---	---	---	5.2
261	---	---	---	0.4	---	---	0.4	---	---	---	1.9	---	---	---	4.6
262	2.4	7.0	2.2	3.2	6.0	3.4	4.0	6.5	6.0	6.5	6.4	7.0	6.2	5.8	4.3
263	---	---	---	0.2	---	---	3.2	---	---	---	7.0	---	---	---	5.2
265	1.8	1.4	0.7	0.4	2.6	3.2	2.4	1.1	8.2	5.8	8.8	6.8	6.8	6.0	5.2
269	4.6	7.6	6.6	1.0	4.4	6.0	1.8	1.8	5.0	9.2	5.9	6.3	6.6	5.6	4.8

TABLE 12

Principal BOD and COD Loadings
Hamilton Harbour

Location	Map (Fig. 1) Reference	Load (10^3 kg/day)
Stelco S. Open Cut Sewer	B	10.1
Stelco N. Trunk Sewer	C	9.9
Ottawa St. Slip*	G	55.5
Dofasco**	I	18.6
Hamilton WPCP	K	4.7

Note: WPCP loading is BOD loading; others are COD loadings

*Includes Stelco E. Side lagoon, hot strip finishing mill, HCl Regen. and 4 Stand Cold Mill, and heavy gauge shear line; and Dofasco Ottawa St. sewer and lagoon.

**Includes Coke oven by-products, Boilerhouse, and Silicon steel plant.

20% BOD removal efficiency at Hamilton WPCP was assumed.

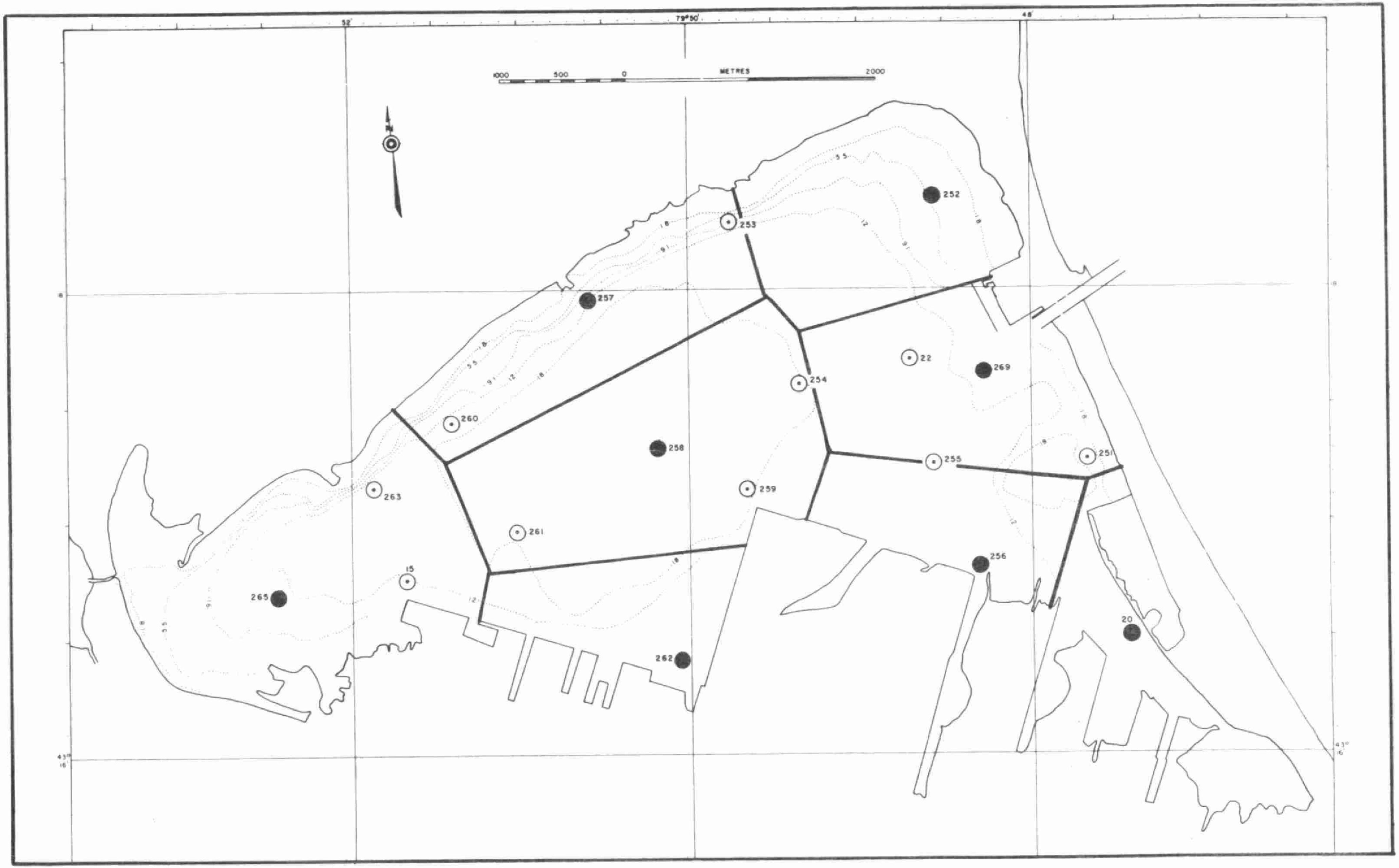

FIGURE I : REGIONS USED IN CALCULATING DISSOLVED OXYGEN STOCK, 8 STATION GRID

D24

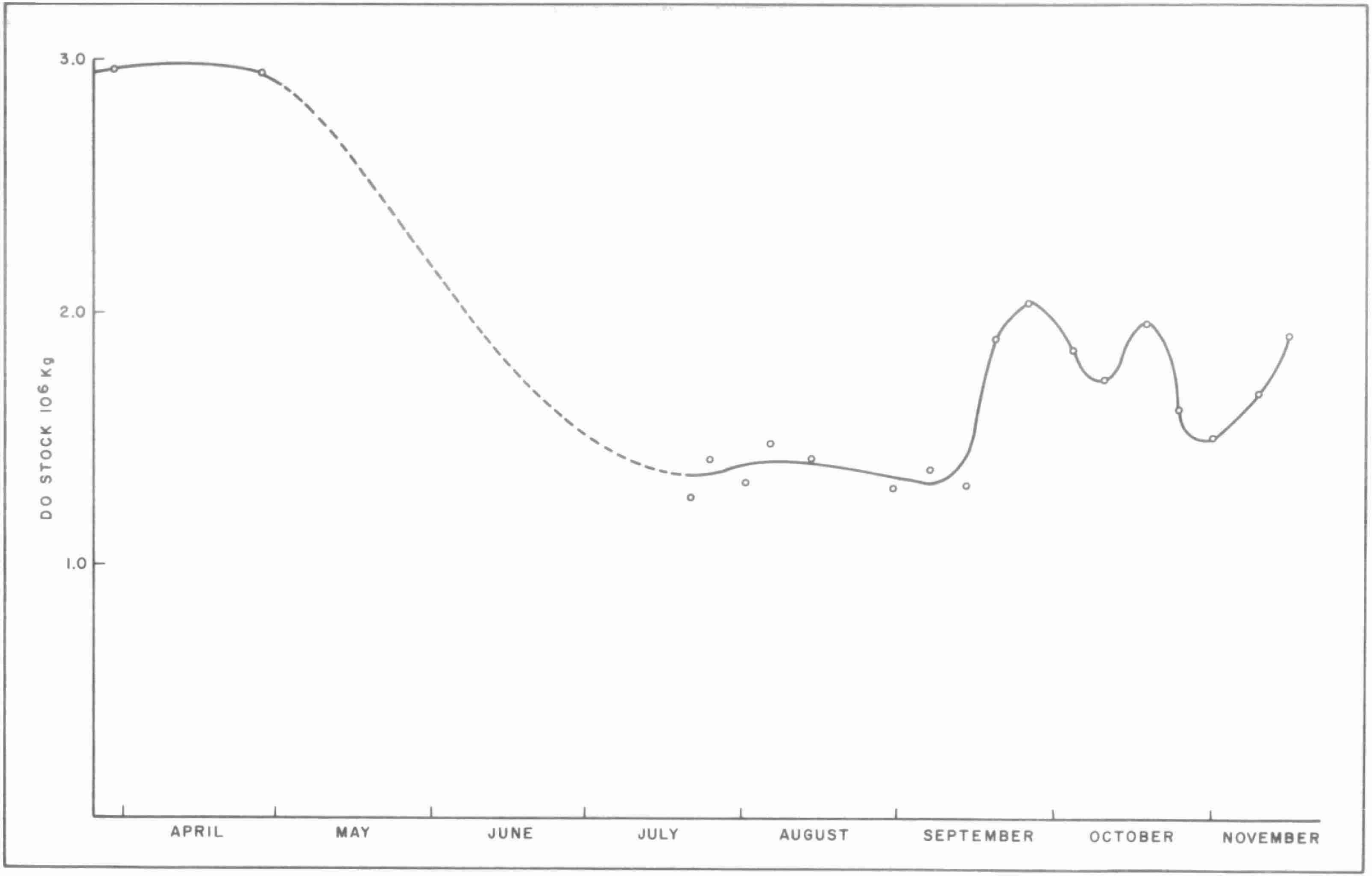

FIGURE 2 DISSOLVED OXYGEN STOCK IN HAMILTON HARBOUR, 1972

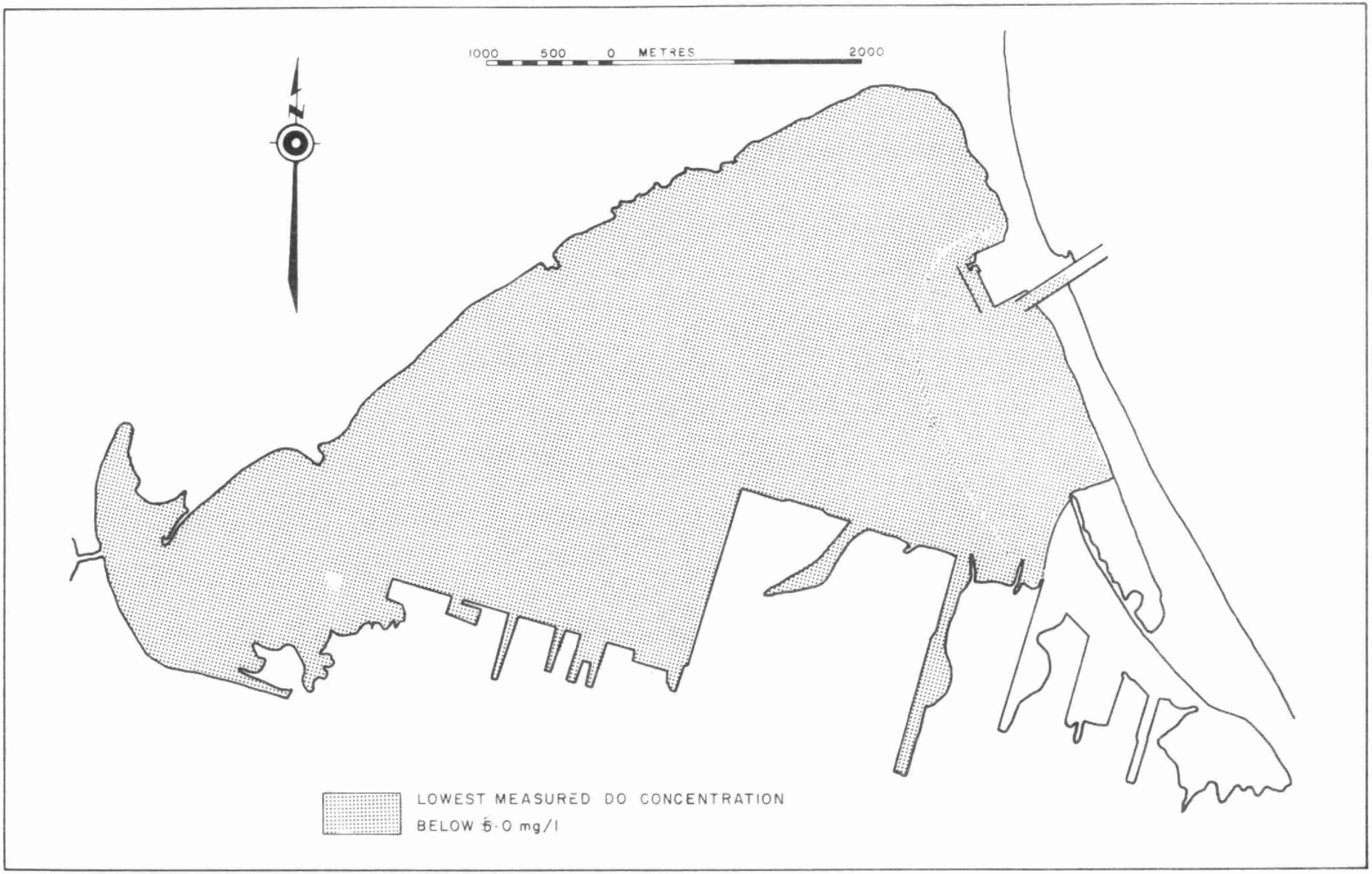

FIGURE 3: MEASURED HYPOLIMNETIC MINIMUM DO CONCENTRATION
JULY 21, 1972

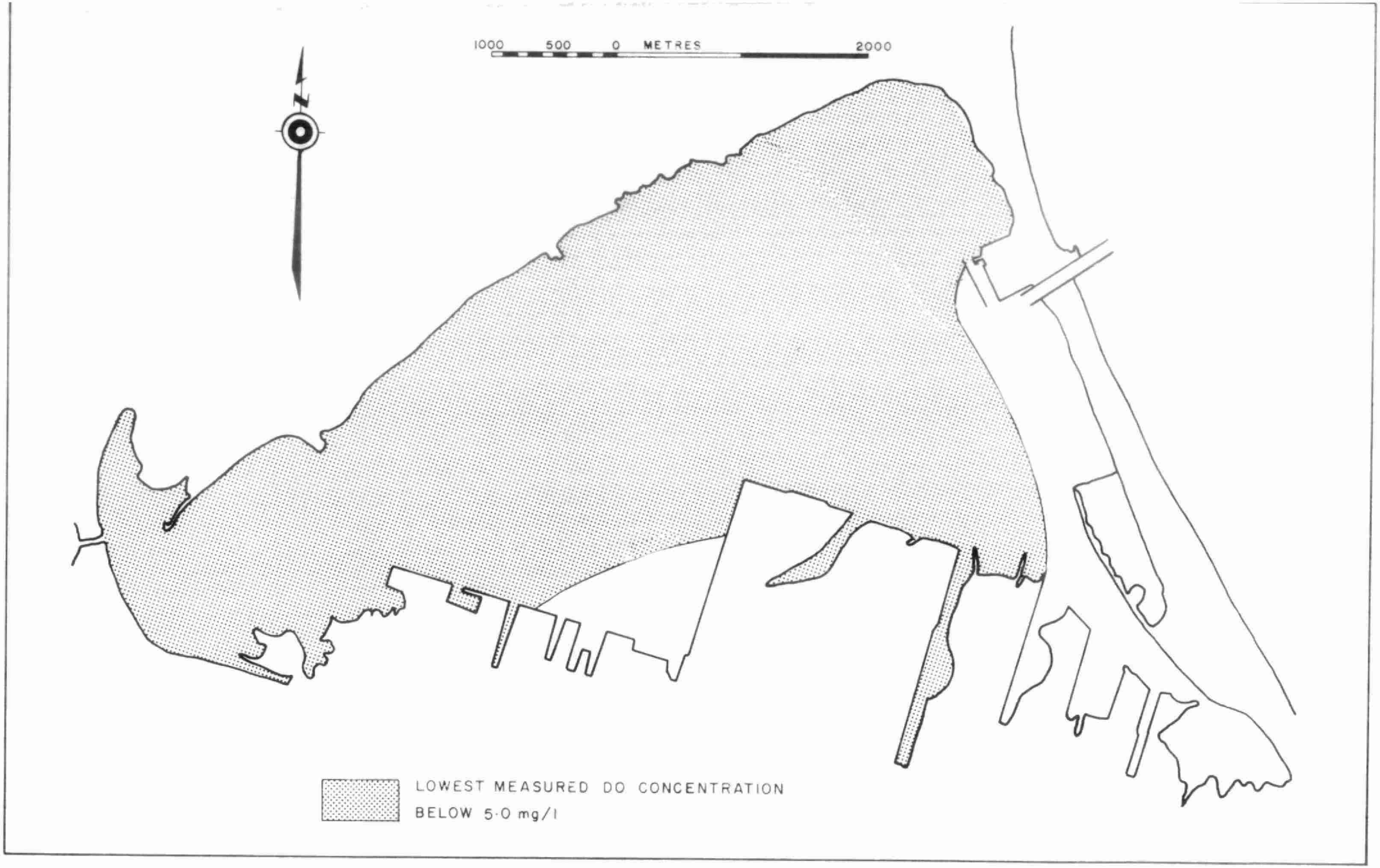

FIGURE 4: MEASURED HYPOLIMNETIC MINIMUM DO CONCENTRATION
JULY 25, 1972

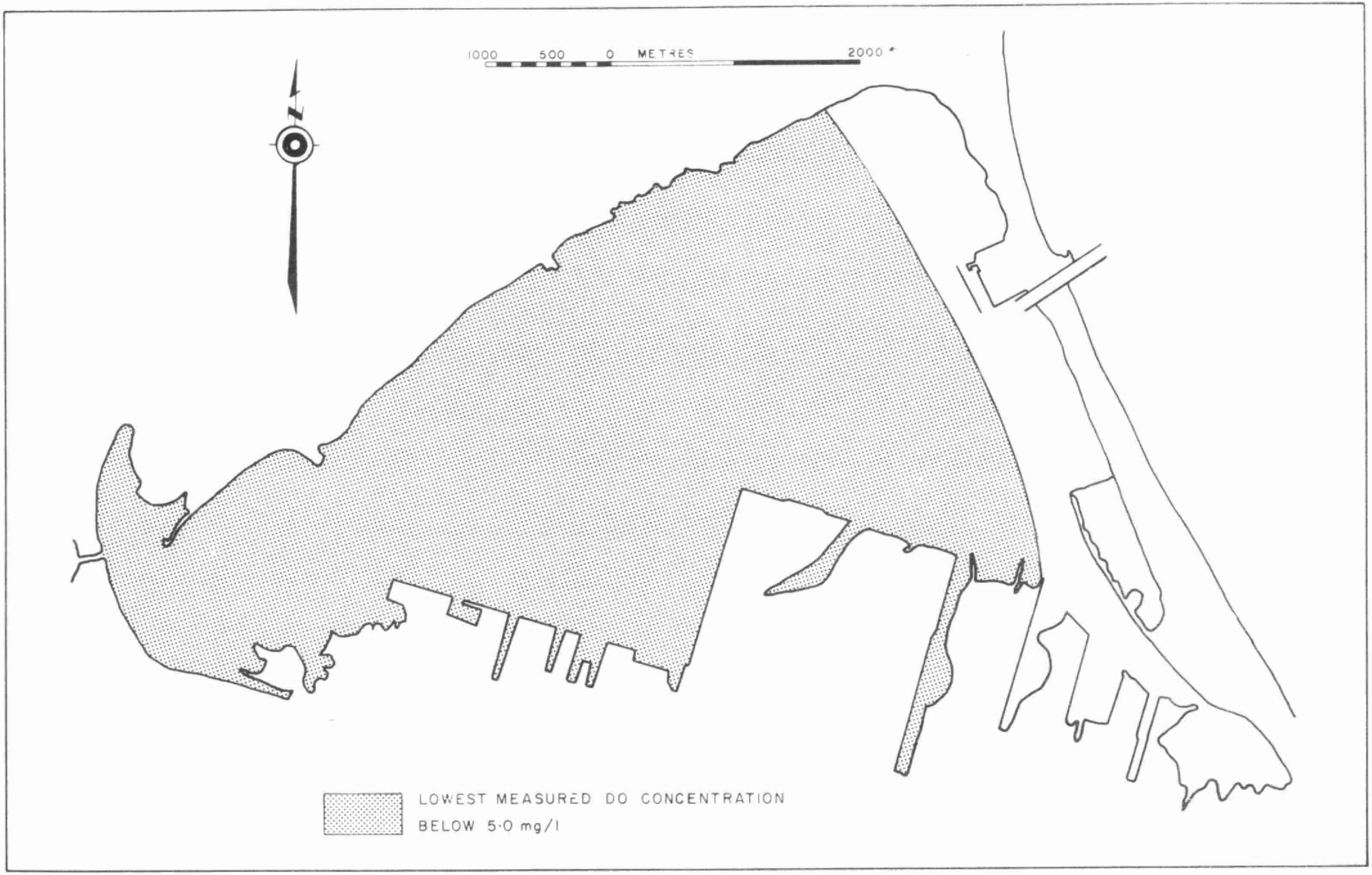

FIGURE 5 : MEASURED HYPOLIMNETIC MINIMUM D O CONCENTRATION
AUG I AND AUG 6-7, 1972

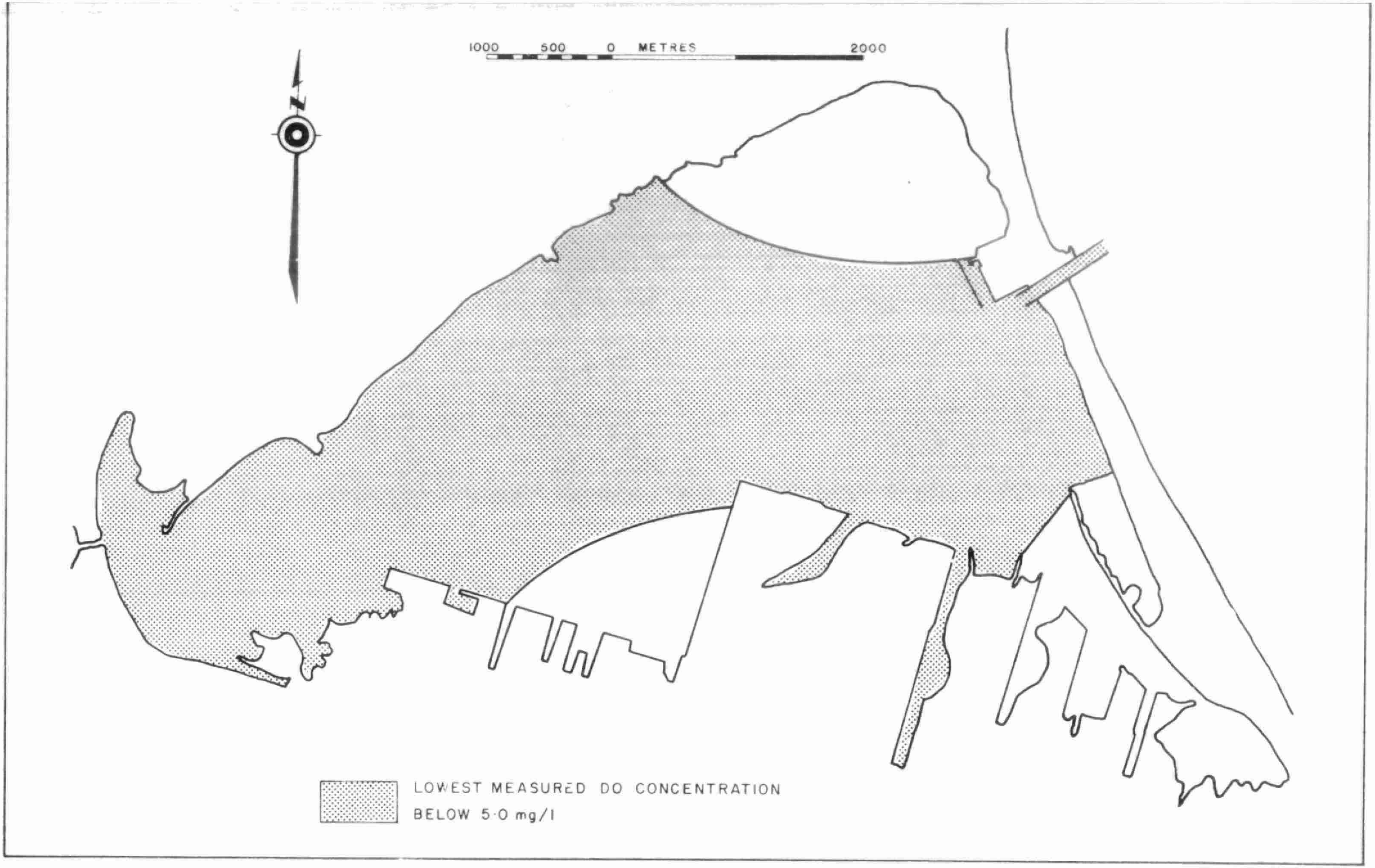

FIGURE 6 : MEASURED HYPOLIMNETIC MINIMUM DISSOLVED OXYGEN CONCENTRATION
AUG. 14 1972

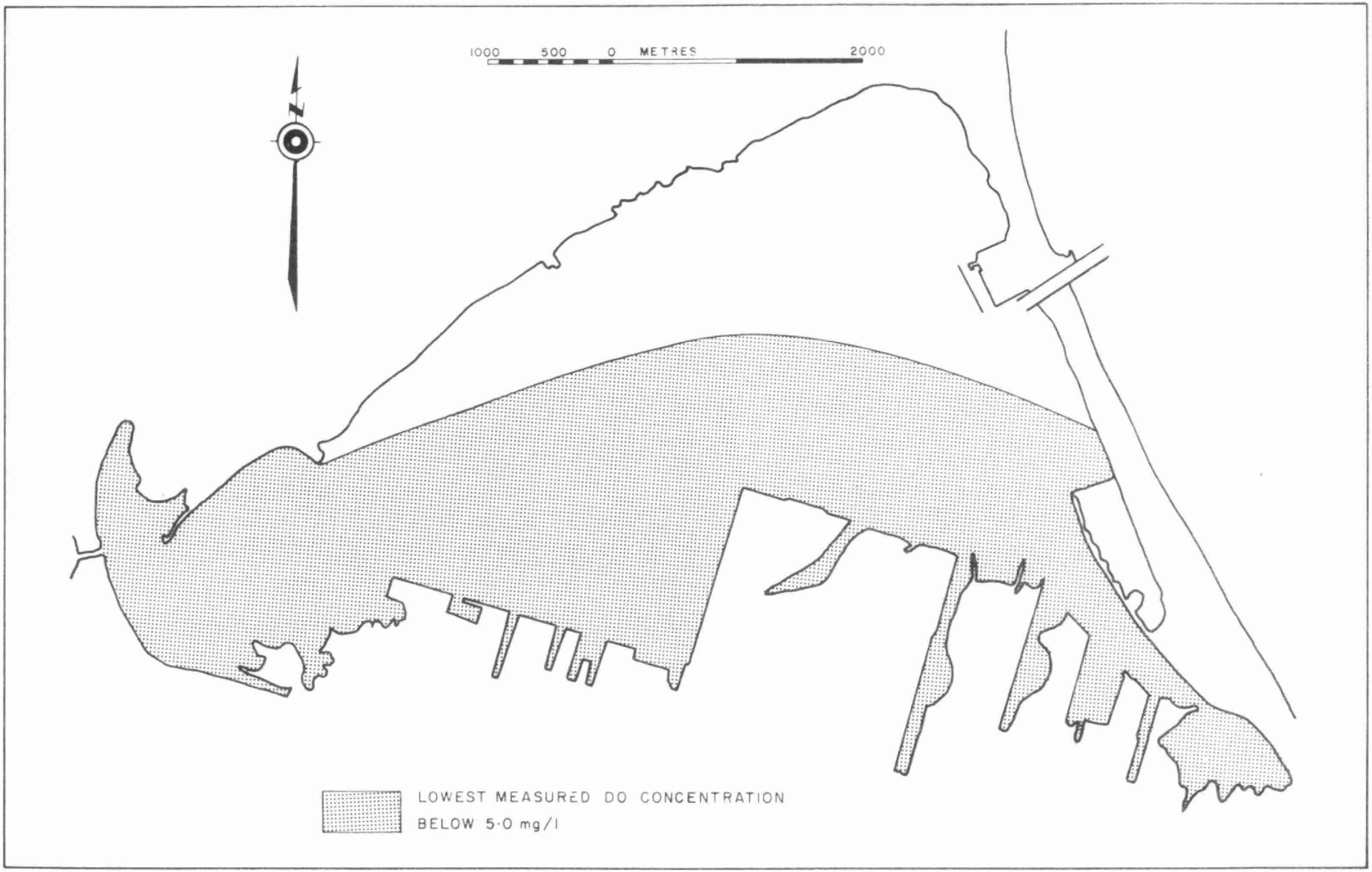

FIGURE 7 : MEASURED HYPOLIMNETIC MINIMUM DO CONCENTRATION
AUG 29, 1972

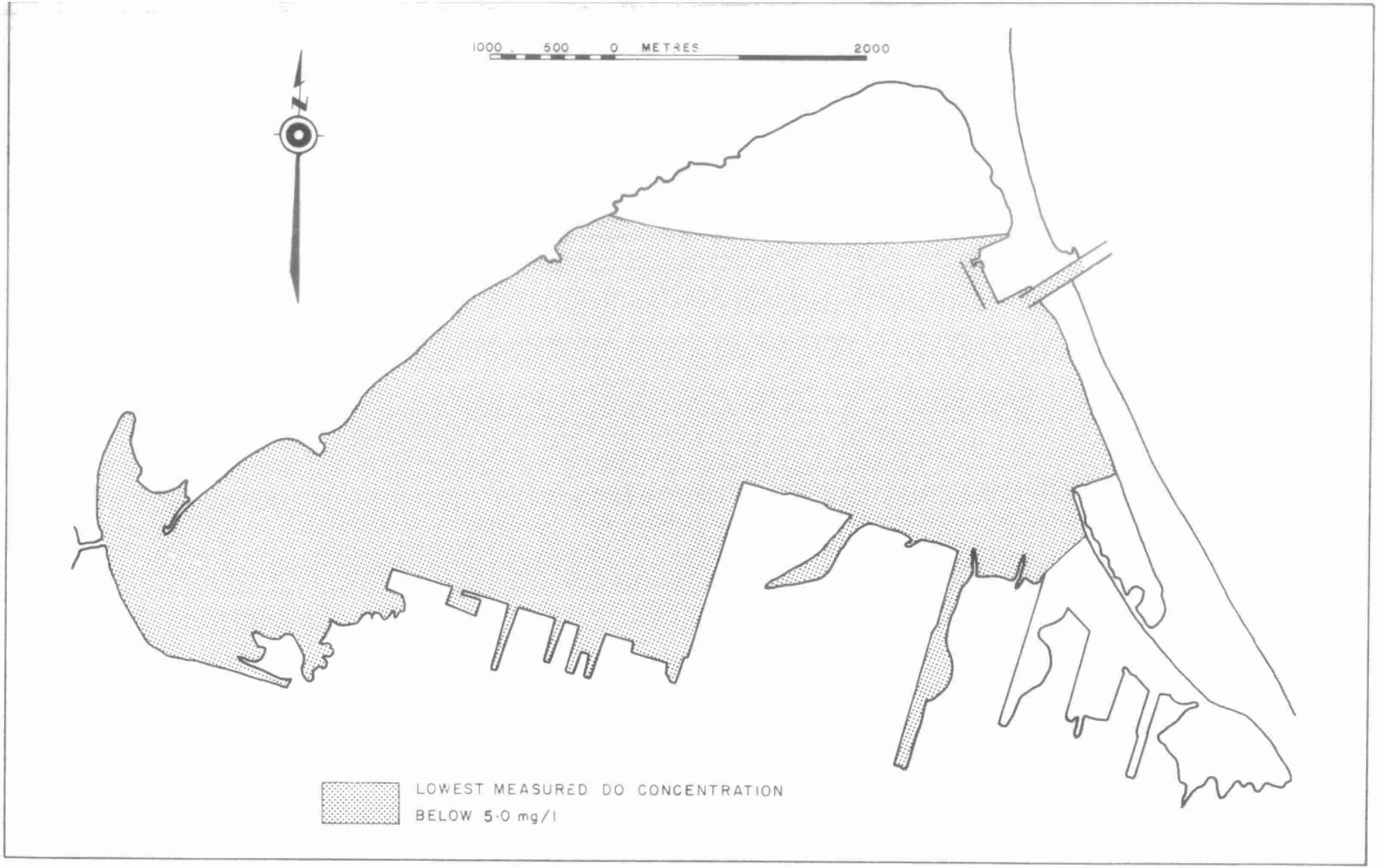

FIGURE 8 : MEASURED HYPOLIMNETIC MINIMUM D O CONCENTRATION
SEPT 5 – 8, 1972

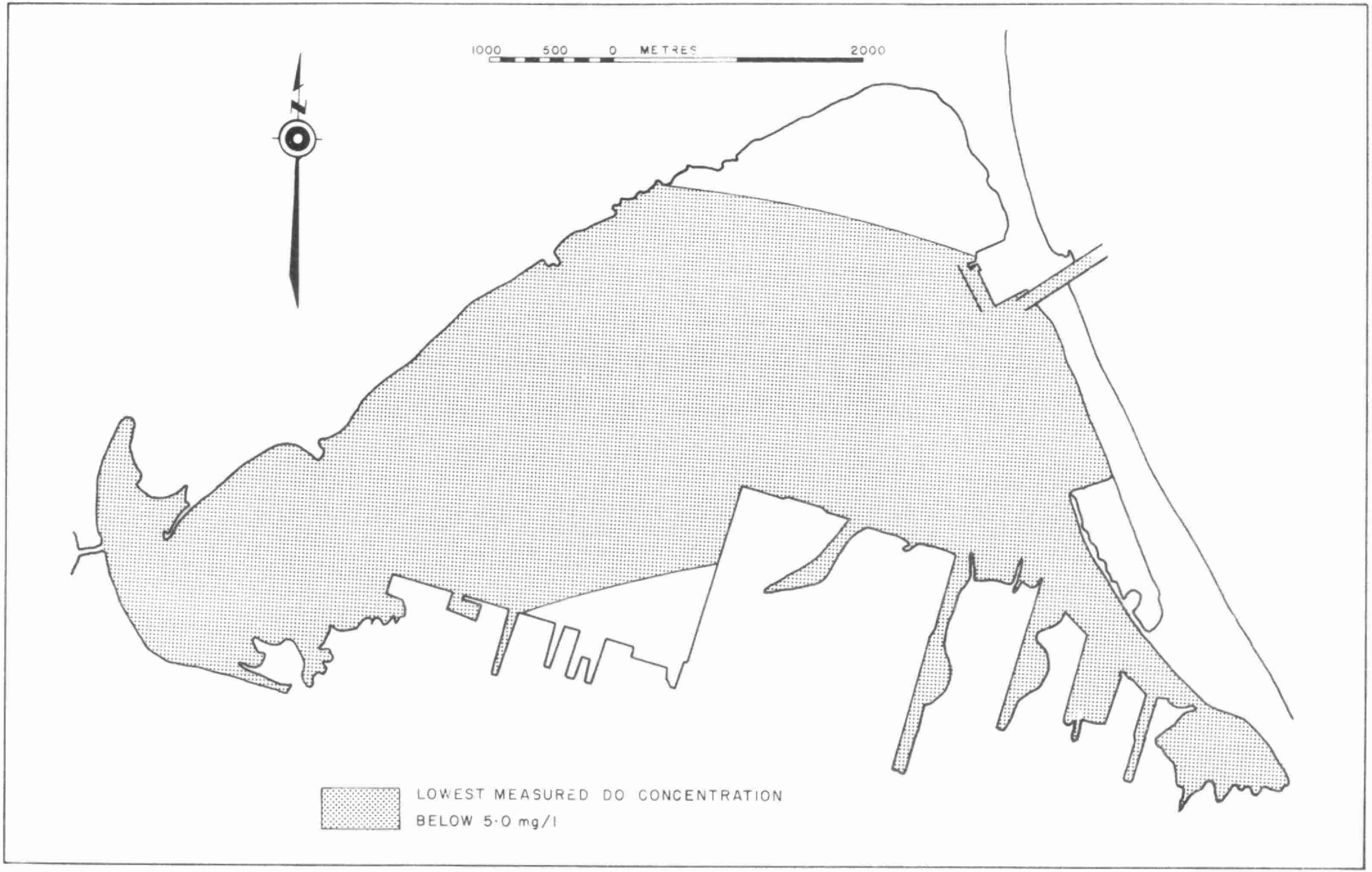

FIGURE 9: MEASURED HYPOLIMNETIC MINIMUM DO CONCENTRATION
SEPT 13 – 14, 1972

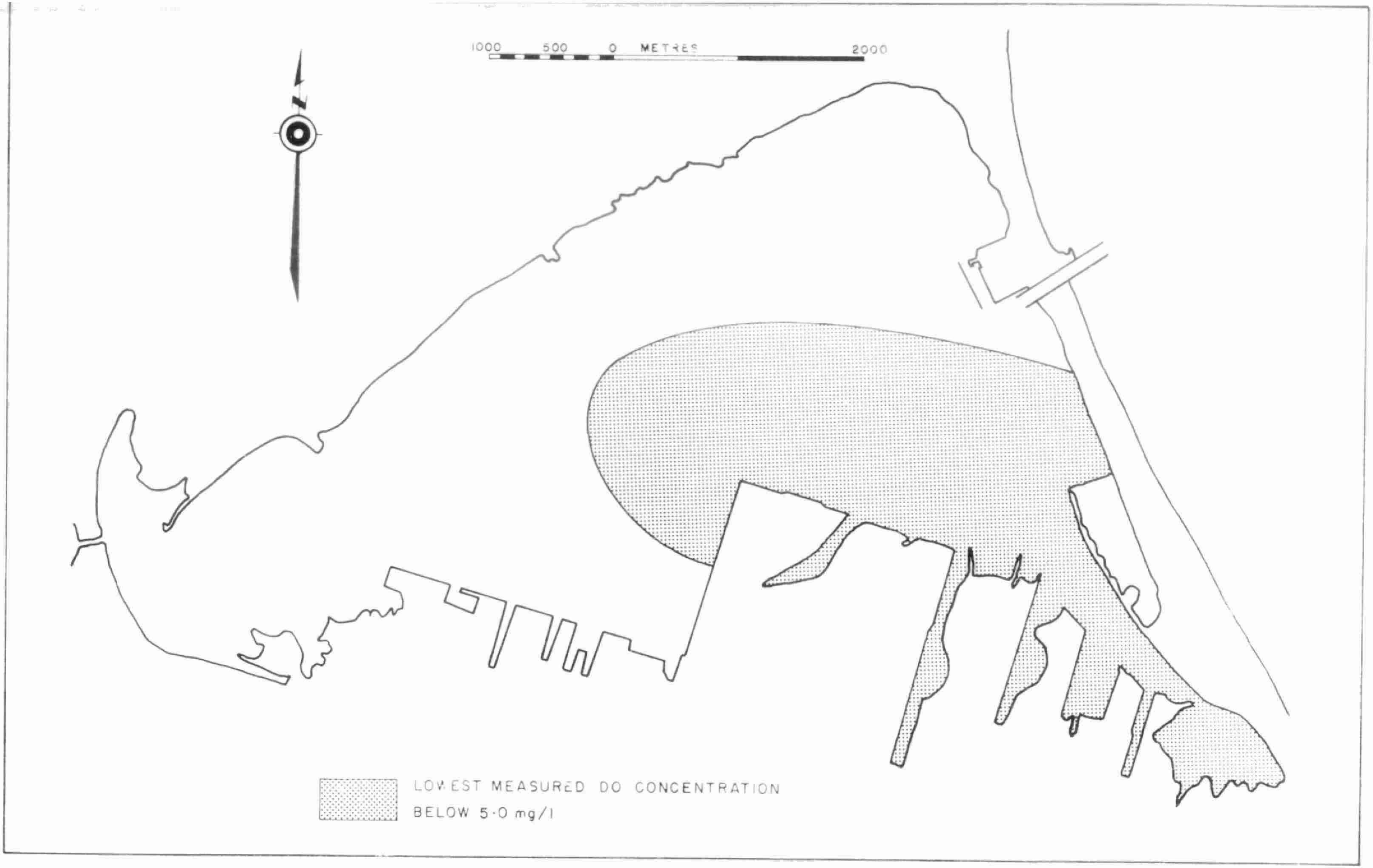

FIGURE 10: MEASURED HYPOLIMNETIC MINIMUM DO CONCENTRATION
SEPT 19 – 20, 1972

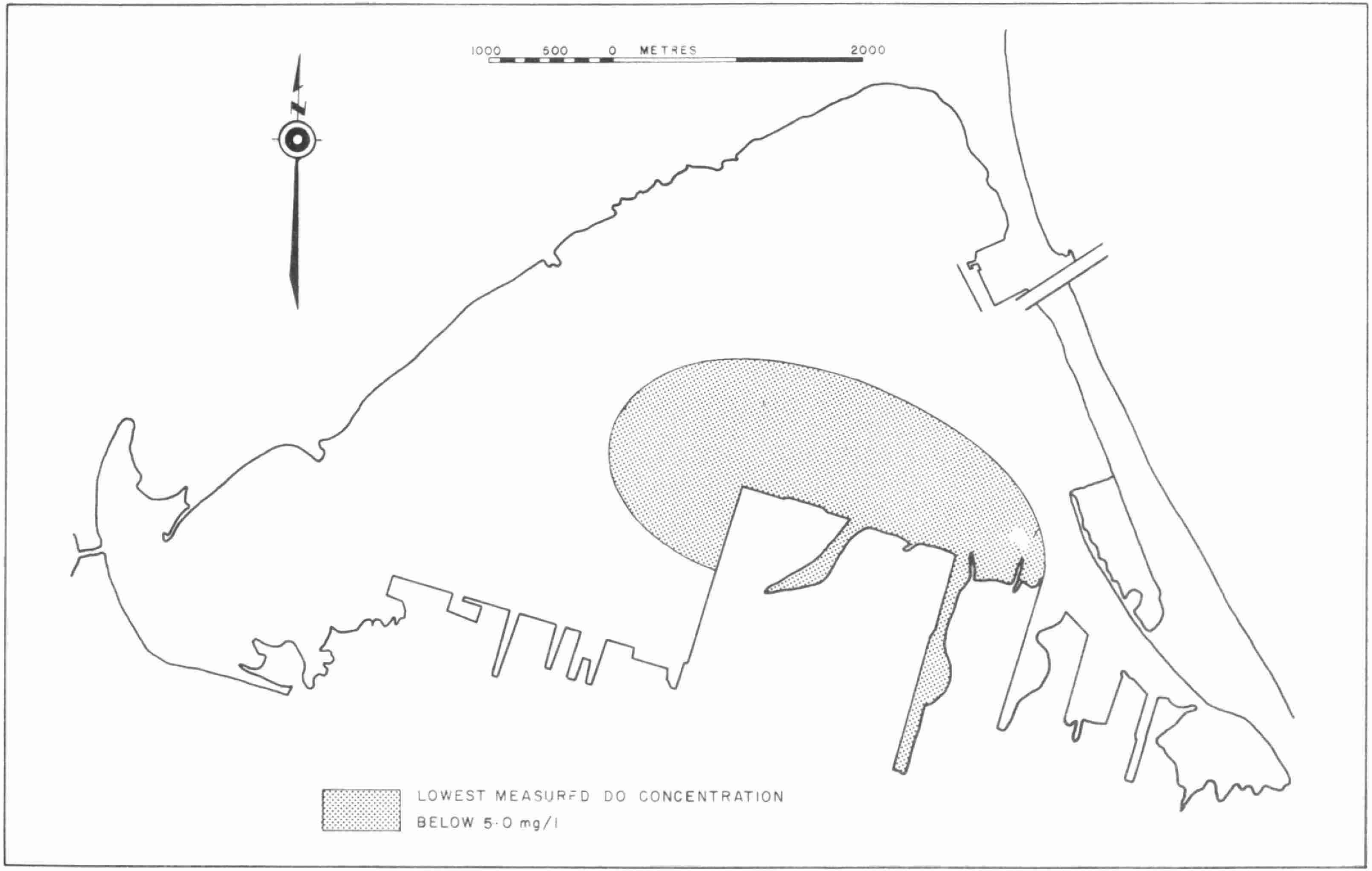

FIGURE 11 : MEASURED HYPOLIMNETIC MINIMUM DO CONCENTRATION
SEPT 25, 1972

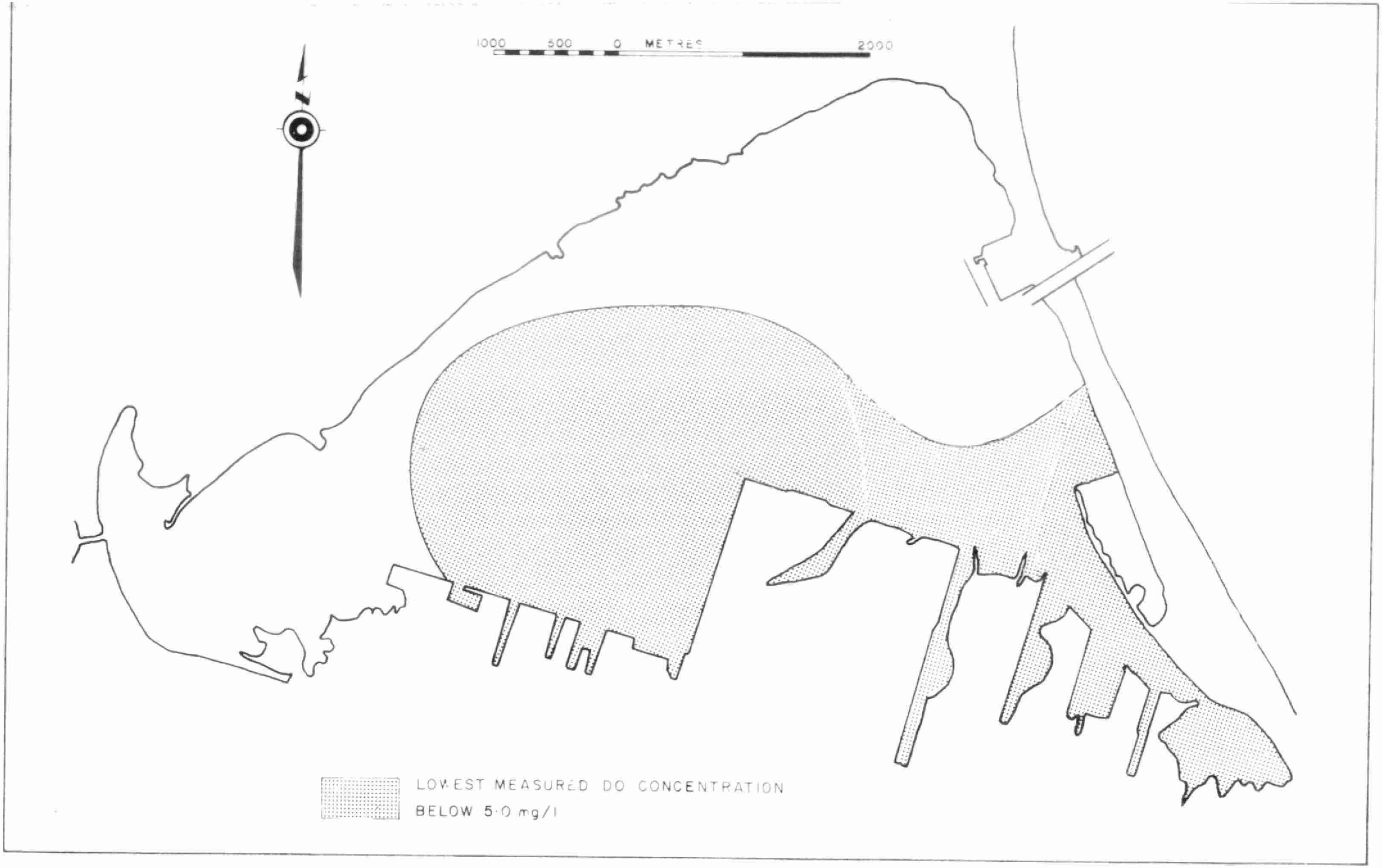

FIGURE 12 · MEASURED HYPOLIMNETIC MINIMUM D O CONCENTRATION
OCT 4–5, 1972

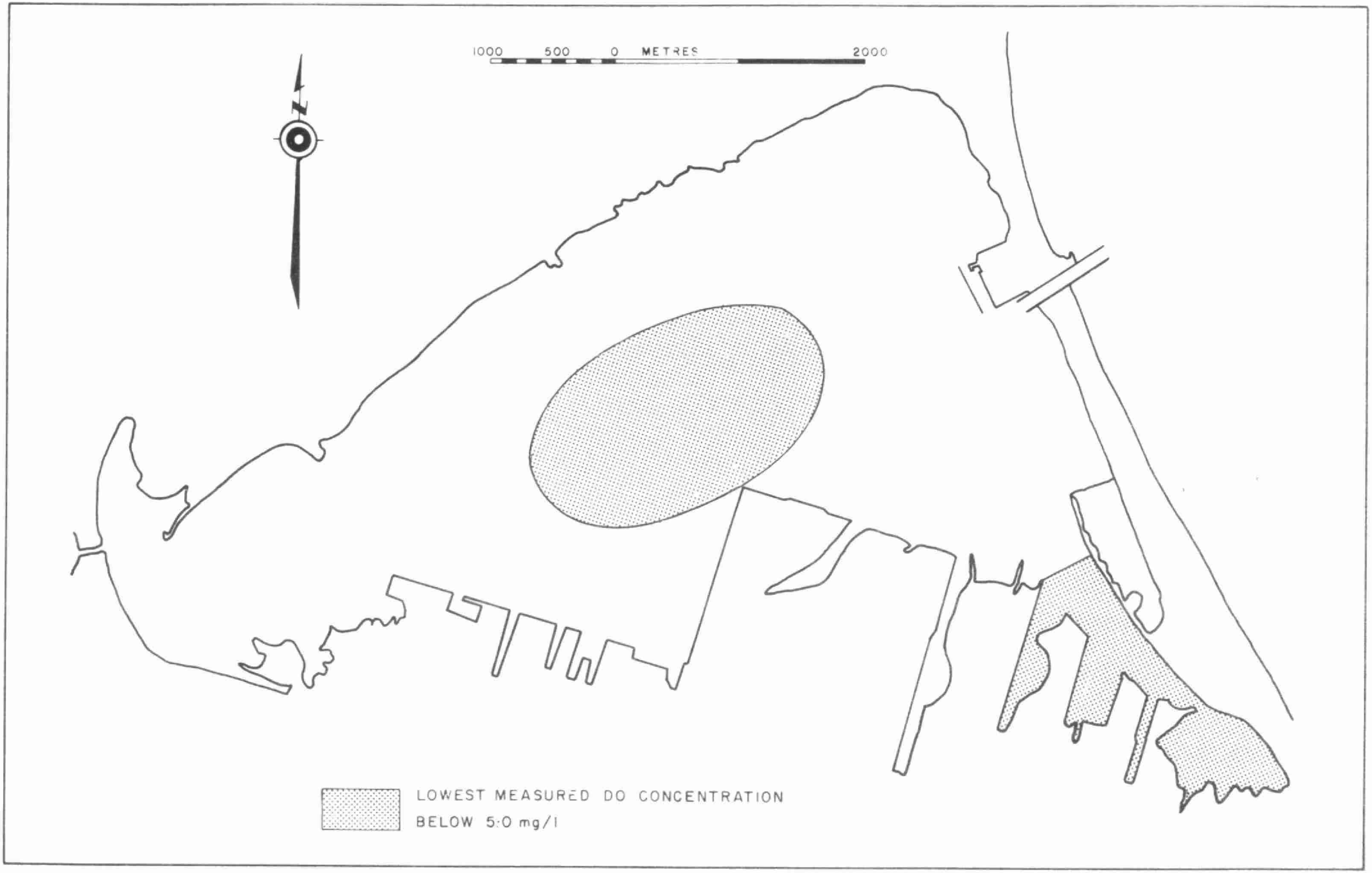

FIGURE 13 : MEASURED HYPOLIMNETIC MINIMUM D O CONCENTRATION
OCT 10, 1972; OCT 18 AND 24 SIMILAR, STATION 20 ONLY

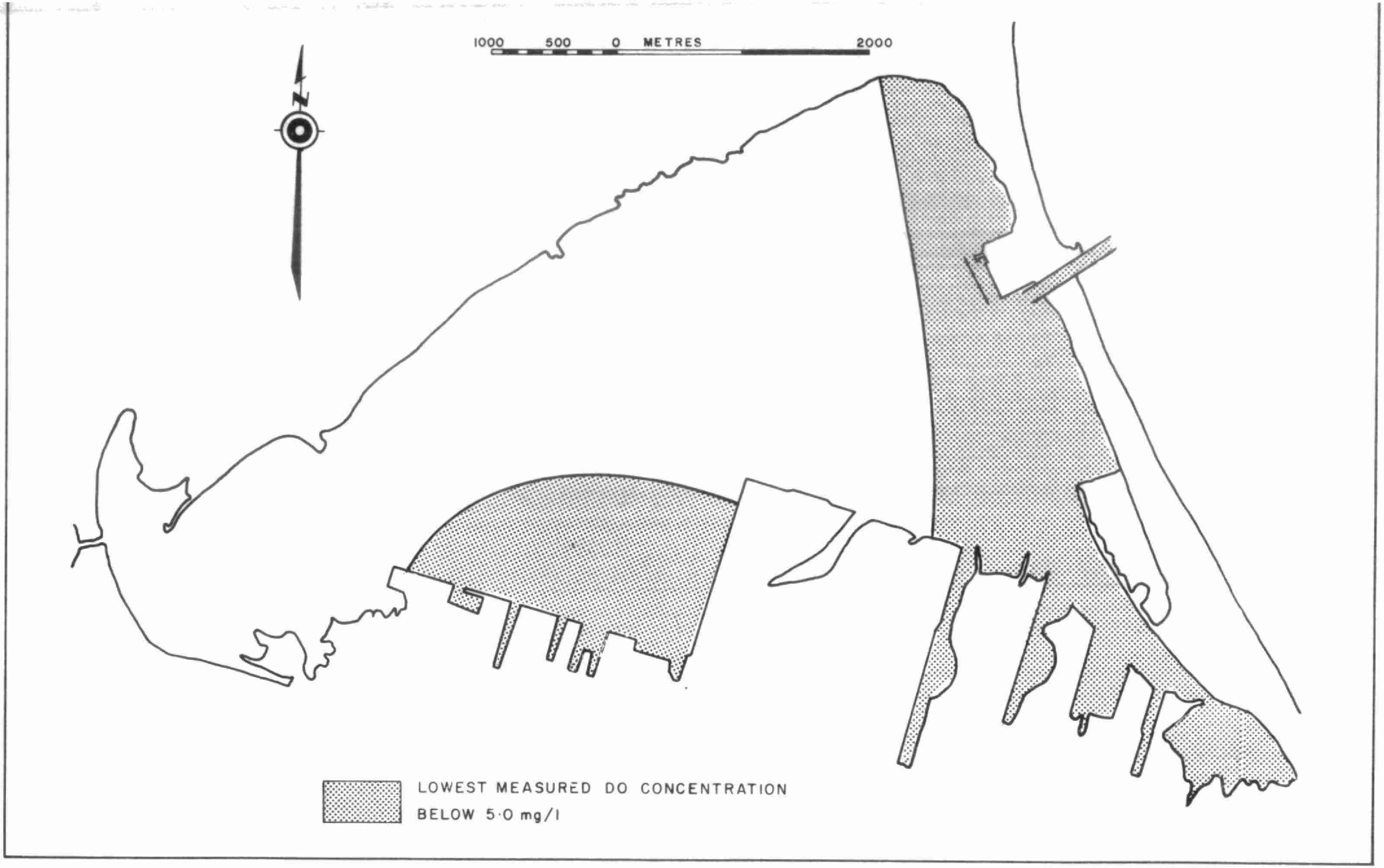

FIGURE 14 : MEASURED HYPOLIMNETIC MINIMUM DISSOLVED OXYGEN CONCENTRATION
OCT.31 — NOV.1 1972

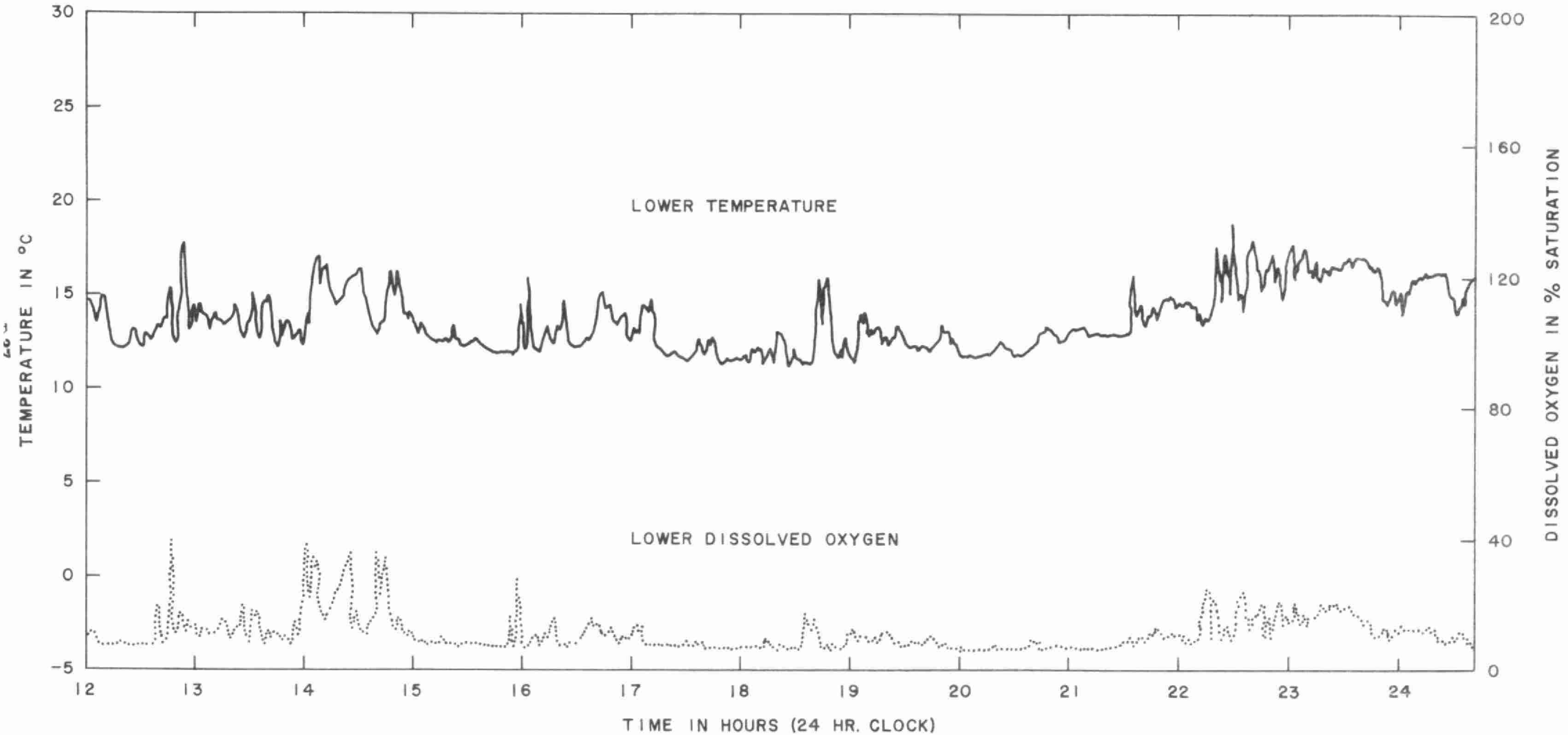

FIG. 15 RECORDING CHEMISTRY METER IN SHIP'S CANAL AUGUST 20, 1973

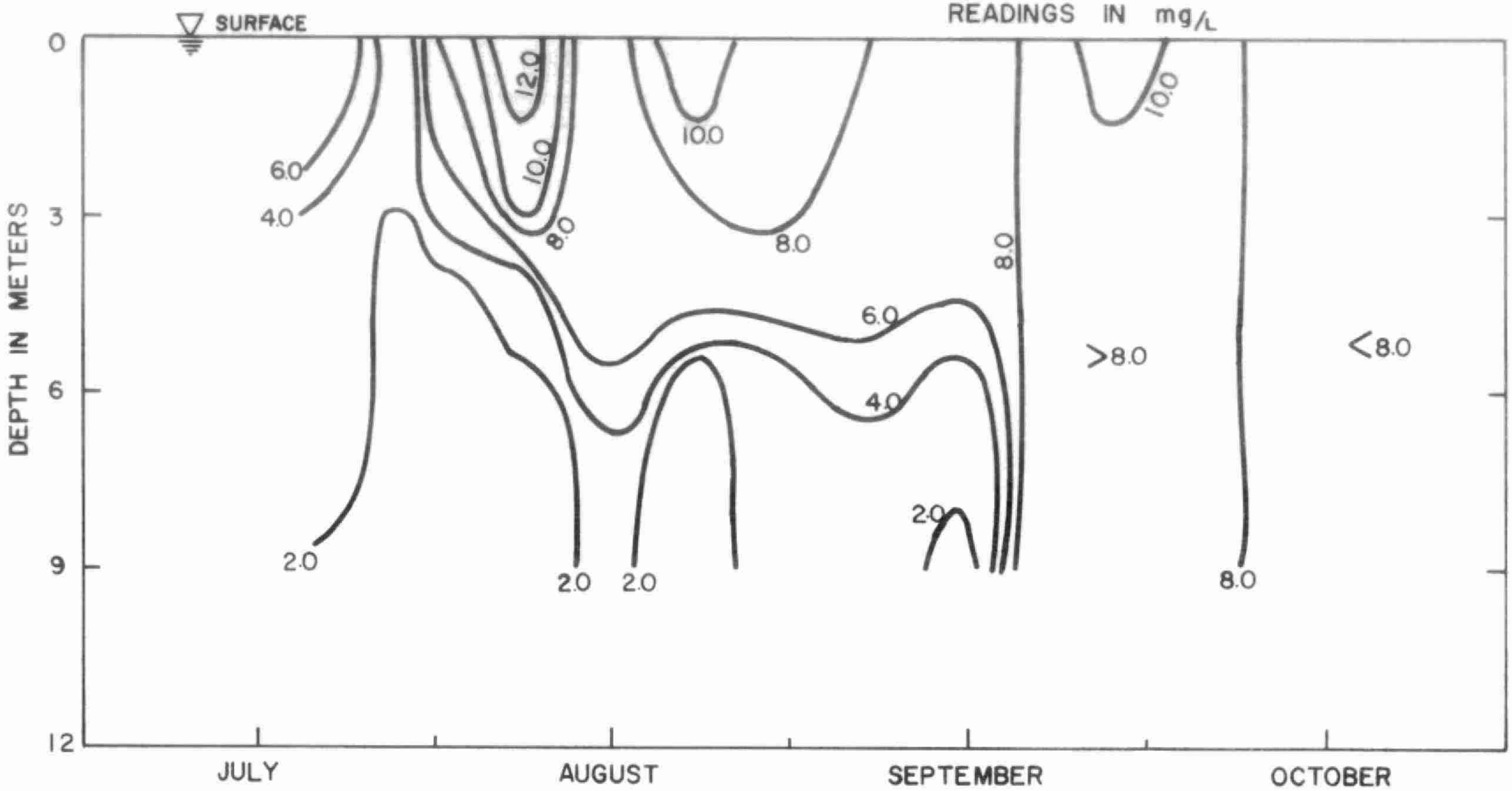

FIG. 16 DISSOLVED OXYGEN ISOPLETHS STATION No. 265

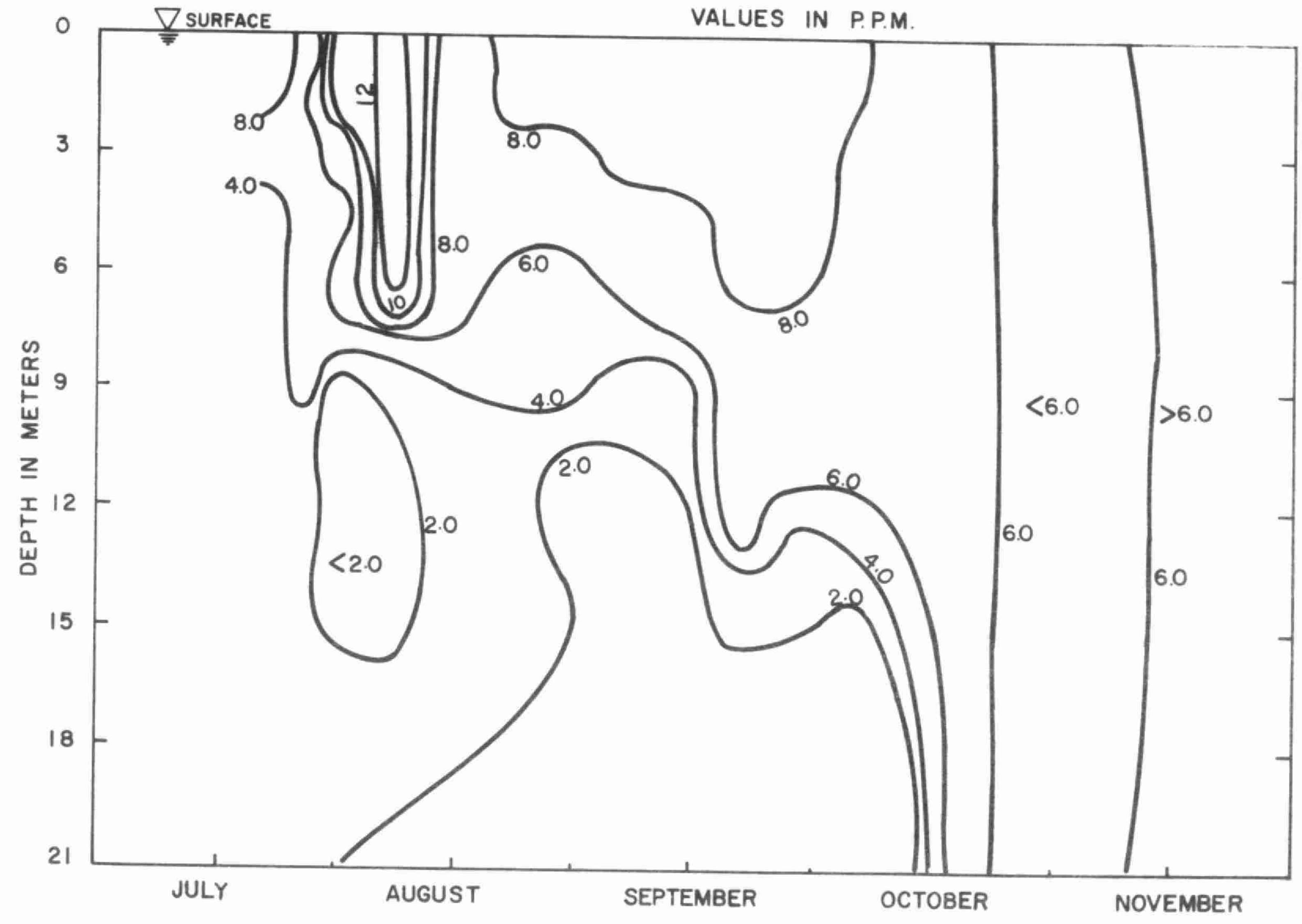

FIG. 17 DISSOLVED OXYGEN ISOPLETHS STATION No. 258

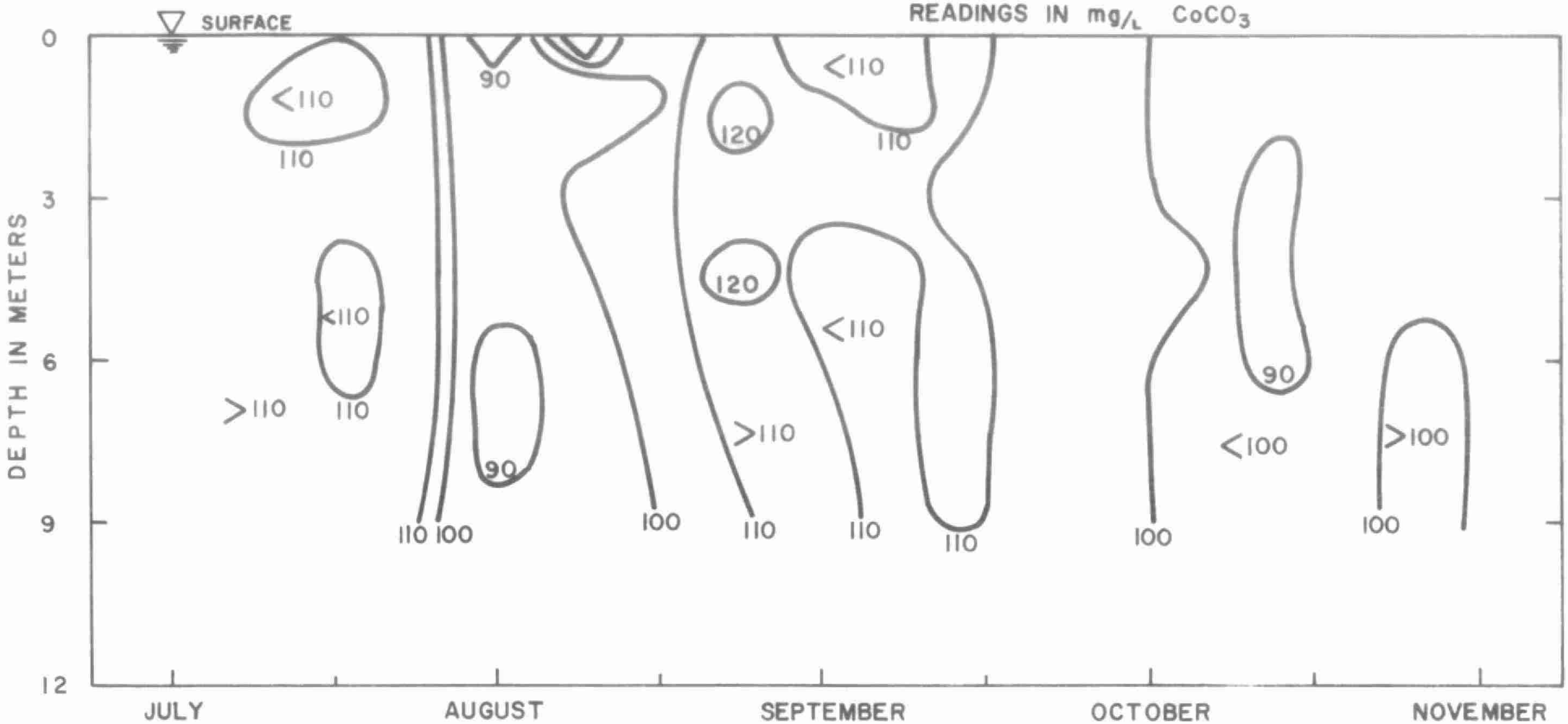

FIG. 18 ALKALINITY ISOPLETHS STATION 265

D40

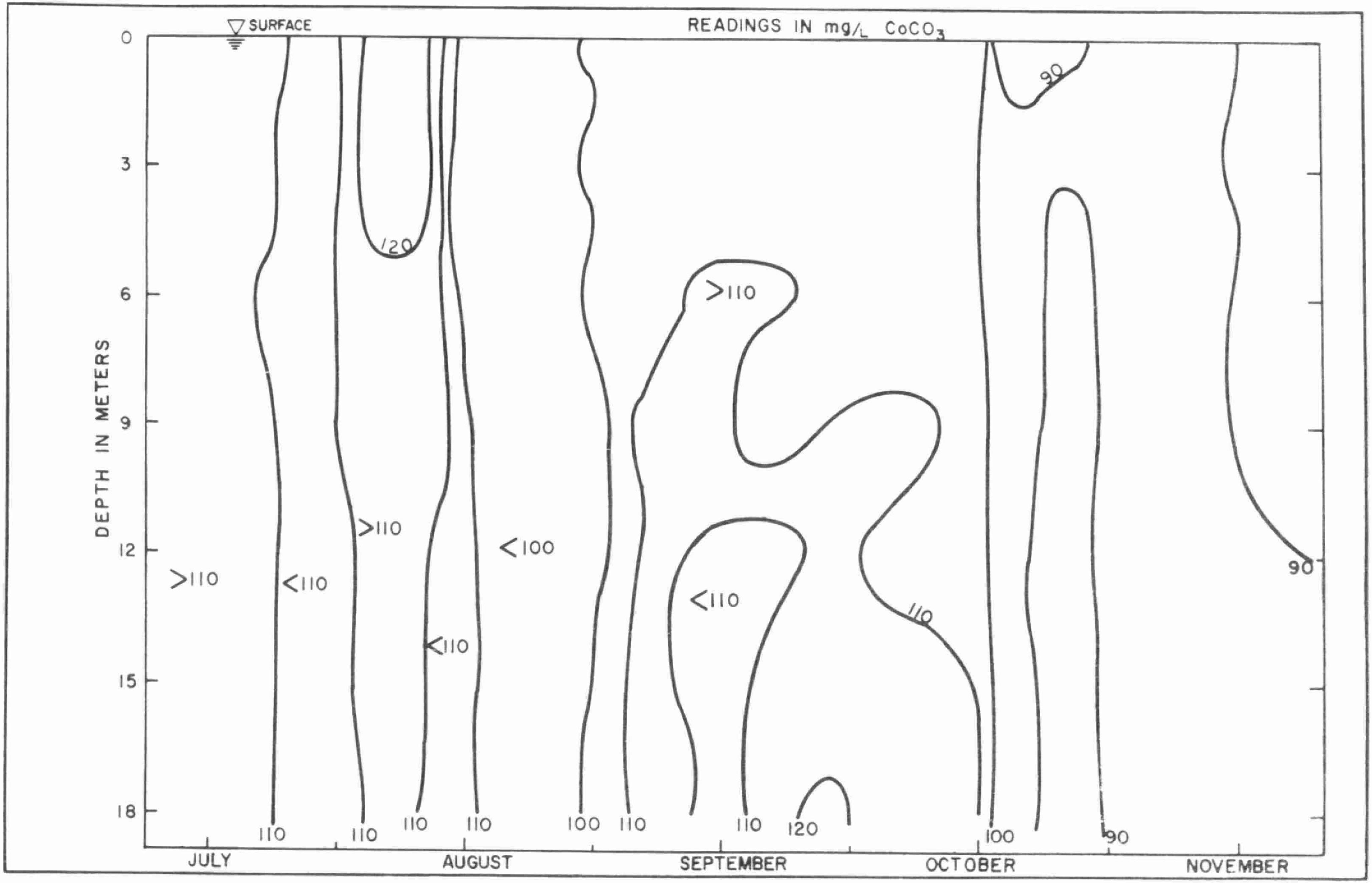

FIG. 19 ALKALINITY STATION No. 258

HAMILTON HARBOUR STUDY

section E

numerical model

HAMILTON HARBOUR STUDY
SECTION E
NUMERICAL MODEL

SUMMARY

A NUMERICAL MODEL IS DEVELOPED WHICH IS CAPABLE OF ASSESSING CHANGES IN WATER QUALITY RESULTING FROM CHANGES IN HARBOUR GEOMETRY, WATER WITHDRAWALS AND WASTE DISCHARGES FOR VARYING METEOROLOGICAL CONDITIONS. THE NUMERICAL MODEL IS A TWO-DIMENSIONAL FINITE DIFFERENCE TIME VARIANT TYPE USING MEASURED DATA AS INPUT VARIABLES. DATA FROM RECORDING CHEMISTRY METERS, CURRENT METERS, WATER LEVEL RECORDERS, WIND RECORDERS AND CONVENTIONAL WATER QUALITY SURVEYS WERE USED AS THE INPUT VARIABLES. THE SENSITIVITY OF THE NUMERICAL SOLUTION TO THE VARIOUS INPUT VARIABLES IS TESTED AND DISCUSSED. THE MODEL SHOWS THAT SOME LOCAL WATER QUALITY DEGRADATION RESULTS FROM ONE REDUCTION OF HARBOUR VOLUME FOR AT LEAST ONE WIND CLIMATE. OF THE METHODS EXAMINED FOR HARBOUR WATER QUALITY ENHANCEMENT A REDUCTION OF LOADINGS OF SIXTY PERCENT AND DESTRATIFICATION WERE MORE EFFECTIVE THAN INCREASING THE HARBOUR-LAKE EXCHANGE RATES.

HAMILTON HARBOUR STUDY

NUMERICAL MODEL

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

HAMILTON HARBOUR

NUMERICAL MODEL STUDY

INTRODUCTION

The Hamilton Harbour study proposal included the development of a numerical type model which could be used to assess the changes in water quality resulting from changes in harbour geometry, water withdrawals and waste discharges for various meteorological conditions. This report outlines the development of the model and discusses some of its limitations. Some test runs of the model for Hamilton harbour using real data are presented.

The model developed is based on a two-dimensional estuarine water quality simulation model developed and initially verified by J.J. Leenderste, 1970 and 1971 (Rand Corporation) in Jamaica Bay, New York City. The model is based on the numerical solution of the coupled equations of momentum, mass transport and continuity. It is a time variant solution where all parameters modelled are integrated with depth. This form of the model was selected initially to minimize both development and computational costs. It was also considered adequate to provide a basis for comparison of different harbour conditions.

It is appreciated that water quality parameters do not have uniform concentrations with depth as stratification exists throughout most of the harbour. However, it is extremely difficult to measure water quality depth concentration profiles and three-dimensional currents on a continuous basis at sufficient locations, to calibrate and verify a three-dimensional model.

The present model predicts concentration contours for specific conductance standardized to 25^{o}C and as such it is a TIME VARIANT DILUTION MODEL. This parameter was selected for initial testing of the model since it is largely a conservative substance (approximately 10 percent being biodegradable dissolved solids). The principal waste discharges in the harbour have elevated conductivities, which are at least twice the levels found in the adjacent lake Ontario (270 umhos/cm) regions, where the conductivity levels are principally a result of dissolved magnesium and calcium bicarbonates.

Some of the major limitations on the model are in the area of computer core and time requirements. The coupling of the time and space step, means that grid spacings of less than 152 meters (500 feet) result in excessively long computer run times, while larger grid spacings would introduce more error in approximating the boundaries. As the model is time variant, input data on waste flows and loadings, meteorological variables, currents and concentrations in the Burlington Ship Canal are required at approximately four minute intervals. The difficulties in obtaining data in this detail are obvious and approximations are required. The model solution also requires input parameters such as dispersion coefficients, bottom roughness factors and wind shear stress coefficients. Determining these parameters for the computational grid is not simply achieved, consequently approximations are necessary. The sensitivity of the model to these approximations individually can be tested, but their combined effect can only be estimated. In the subsequent section, "Input Variables", the various model input variables are discussed and the model tested for its sensitivity to each variable separately. The section "Survey Data", compares the model results with survey data to determine how representative the model predictions are of the harbour processes.

It is immediately apparent that the number of variations possible for the input variables to the model is extremely large and it is necessary to carry out selective runs. Indeed the difficulty in defining some of the input variables discussed in the preceeding paragraph further suggests only selected computer runs are warranted. However, any selective model testing may omit some critical cases; consequently it was decided to test the model in a comparative (qualitative) manner by varying only one input at a time then observing the model results.

Spectral analyses of continually recorded water chemistry and current data in both the Burlington Ship Canal and the harbour indicate the longest period with a statistically significant variance density concentration was 17 hr. Consequently the model was generally run for about 20 hr. which would include the major periodicities without excessive computer times. Some testing of longer and shorter periods were carried out and are noted in the text.

THEORETICAL BACKGROUND

The equations used in the model are the two-dimensional forms of the continuity, momentum and mass balance equations which describe the variation of the fluid velocity field and the transport of contaminants.

Momentum Equation

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} - fV + g\frac{\partial \zeta}{\partial x} + g\frac{U(U^2+V^2)^{\frac{1}{2}}}{C^2 H} - \frac{\tau_X^S}{\rho H} + \frac{US}{H} = 0 \qquad (1)$$

(A) (B) (C) (D) (E) (F) (G) (H)

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} + fU + g\frac{\partial \zeta}{\partial Y} + g\frac{V(U^2+V^2)^{\frac{1}{2}}}{C^2 H} - \frac{\tau_Y^S}{\rho H} + \frac{VS}{H} = 0 \qquad (2)$$

where U = integrated velocity in X direction
t = time
V = integrated velocity in Y direction
f = Coriolis parameter
g = acceleration due to gravity
C = chezy coefficient representing bottom friction
H = depth = ζ + reference depth
S = source term
ζ = elevation above reference depth

τ_X^S = component of the wind stress in X direction

τ_Y^S = component of the wind stress in Y direction

(A) momentum change with time in X direction
(B) momentum change due to variation of velocity in X direction
(C) momentum change due to variation of velocity in Y direction
(D) momentum change due to earth's rotation
(E) momentum change due to water level change
(F) momentum change due to bottom friction
(G) momentum change due to wind drag on the water surface
(H) momentum change due to addition of water from outfalls

Continuity Equation

$$\underset{(A)}{\frac{\partial \zeta}{\partial t}} + \underset{(B)}{\frac{\partial (HU)}{\partial X}} + \underset{(C)}{\frac{\partial (HV)}{\partial Y}} = \underset{(D)}{S} \qquad (3)$$

(A) change in volume with respect to time from water levels
(B) change in volume due to velocity and depth changes in the X direction
(C) change in volume due to velocity and depth changes in the Y direction
(D) change in volume due to intakes or outfalls

Mass Balance Equation

$$\underset{(A)}{\frac{\partial (HP)}{\partial t}} + \underset{(B)}{\frac{\partial (HUP)}{\partial X}} + \underset{(C)}{\frac{\partial (HVP)}{\partial Y}} - \underset{(D)}{\frac{\partial (HD_x \frac{\partial P}{\partial X})}{\partial X}} - \underset{(E)}{\frac{\partial (HD_y \frac{\partial P}{\partial Y})}{\partial Y}} - \underset{(F)}{HS} + \underset{(G)}{KHP} = 0 \qquad (4)$$

where P = mass concentration

D_x= dispersion coefficient in X direction

D_y= dispersion coefficient in Y direction

S = sources or sinks for mass P

The terms of equation 4 are:

(A) change of total mass with time
(B) change of mass flow in X direction
(C) change of mass flow in Y direction
(D) change of mass due to dispersion in X direction
(E) change of mass due to dispersion in Y direction
(F) mass added or subtracted due to sources or sinks

(G) change of mass due to environmental reactions (e.g. reaeration, biological assimilation, sedimentation, etc.)

Method of Solution

These coupled equations can be solved numerically in a time-space field. The finite difference forms of the equations are presented in Appendix 1, and represent the parameters at points on a space and time staggered grid as follows:

```
k +1 + - + - +
     1 0 1 0 1
k    + - + - +
    j-1  j  j+1
```

where + water level above datum ζ and pollutant concentration P

O datum water depth

\- U velocity

1 V velocity

This scheme has the advantage that on the formula operated on in time, there exists a centrally located spatial derivative for the linear term. The finite difference scheme operates on two half time steps to each whole time step. The U - velocity, water elevation and pollutant concentration are calculated in the first half step, while the V - velocity is calculated and the water elevation and pollutant concentration are recalculated in the second half step. Other advantages to this scheme are that it is not dispersive or dissipative. That is, the solution scheme does not cause the pollutant to disperse without physical cause, nor does it cause them to decay without reason.

The procedure for utilizing the finite difference scheme in the prediction of water quality is as follows:

1. A grid in the format shown above is superimposed on a marine chart such that the harbour entrance (i.e. Burlington Ship Canal) is oriented along a row on the left hand boundary. The coastline is approximated by drawing straight line through appropriate datum water depth points (i.e. 'O'). This procedure ensures that at all land boundaries, either the U velocity or the V velocity component is zero. The water depths are transferred from the marine chart to the appropriate 'O' points on the grid. The outfalls are

assigned to an appropriate '+' point on the grid and the flows are converted to an equivalent increment in elevation for a grid area equal to square enclosed by the "0's".

2. In the first half time step the equations of momentum in X-direction and continuity are solved simultaneously followed by the solution of the mass transfer equation. From the continuity equation, it can be found, using the appropriate finite difference approximations (Appendix) that for any given '+' point, the water elevation may be found, for time 't+½', to be a function only of two other unknowns on the same row: the U velocities adjacent to it on either side at time 't+½'. Similarly, for the momentum equation the U-velocity for time 't+½' can be found in terms of the adjacent unknown water levels on each side at time 't+½'. If the solution proceeds from the left boundary, the boundary value is known and the equations for the U-velocity and water elevation can be reduced to just two unknowns. Or in other words by solving alternately the continuity and momentum equations across a row with a known left hand boundary then a series of recursion equations relating the U-velocity to the unknown elevation on its right and the water elevation to the unknown U-velocity on its right can be found. Since a right hand boundary value is also known, then it is possible to work back across the row from right to left using the recursion equations alternately to find the U-velocities and water elevations for that row for 't+½'. Solution proceeds in this manner from row to row until all the U-velocities and water elevations for time 't+½' are known. A similar method is used for the solution of the mass transfer equation. A more complete description of the method is found in the Appendix.

3. A similar procedure to the above is used with the continuity and Y-momentum equations and is applied to the columns, which gives the V-velocity and water elevation at time 't+1'. The mass transfer equation is again solved in the same manner but using columns instead of rows.

INPUT VARIABLES

Time Period of Model Tests

As the model is not steady state it is necessary to examine the effects of running the model for various time periods. Figure 12 shows the model predictions for the regular case for 20, 36 and 48 hours. In this figure it is observed that the shape of the concentration contours is generally maintained but extends over more of the harbour. All the runs were made for 16, 20 or 40 hours appreciating that any of these periods will produce the same general shape of concentration contours for same input data. Comparisons of different values for the input variables were always run for the same time period.

Harbour Boundaries

The computational grid appears in Figures 1 and 2. Figure 1 represents the model boundaries approximating Ministry of Natural Resources aerial photography for August 4, 1972, with the computational grid superimposed. Figure 2 represents the model boundaries approximating the proposed land filling with the computational grid superimposed. The bottom contouring is from Great Lakes data. Figure 14 shows the model boundaries minus the Harbour Commissioners filling along the Burlington Skyway.

Wind Climate

The wind climate is a current generating mechanism in the momentum equation through the water surface wind stress coefficient. Time histories of the wind vector as measured at the Hamilton Airport (Table 1) were used as an input to the numerical solution. While the wind stress coefficient is conceptually straightforward, the determination of a meaningful value for the coefficient presents some difficulties (Hidy, 1972; Keulegan, 1951). In the case of Hamilton harbour even where the fetches are short in any direction it was considered that the wind stress on the harbour surface would be one of the more significant current generating mechanisms. A mean statistical value for light winds was used for the coefficient. Different values were not tried. However, the sensitivity of the model to changes in wind direction was determined. Figure 9 shows the currents after 26.6 hrs with the winds from the North and Northwest or 180 degress from those in Figure 4 where the winds are from the South and Southeast. Both the wind stress coefficient and wind speed magnitudes are the same in Figures 4 and 9. The resulting changes in the conductivity level configuration and the currents appear in Figure 8.

The secondary effects of the wind climate on the circulation patterns in the harbour are represented by the time histories of the water levels or currents in the Burlington ship canal. These variations are caused by the combined effects of winds on the harbour water and the changes occurring on the lake Ontario side of the ship canal due to lake effects. These effects are applied to the model as a boundary condition which is time varying.

Current Patterns

The characteristics of the currents in the harbour were determined by operating two recording current meters at two different depths and conducting some areal surface current measurements. The two recording current meters were operated from December 14, 1972 to February 3, 1973 (Figure 17). An ice sheet existed over the meters during most of December. A time series analysis of the records indicate similar periodicities as those recorded by the ship's canal instrumentation. (The time variation is discussed in detail in Section A.) A statistical analysis of the data shows a mean speed of 3.6 and 2.2 cm/sec at 16.1 and 6.1 meters from the bottom, predominantly towards the North (Table 5). Periods of little or no movement were 4 and 5 percent at the 16.1 and 6.1 m depths. This indicates a reasonably active velocity regime at depth not unlike many of the near shore regions of lake Ontario. Depth samplings of water chemistry also suggest the harbour is an active internal wave region (with reflections) as thermal and chemical stratification are both time variant during appropriate wind climates and not necessarily coincident. One expects a reasonably well defined velocity field in the harbour and some success with a modelling approach which utilizes a depth integrated velocity field.

The areal velocity field (Figure 18) was sampled during different wind conditions with a fast boat, basically at one depth (1.5 meters below the surface). While the surveys were limited, it was demonstrated that a velocity field existed throughout most of the harbour. A mean speed of 5.6 cm/sec was found, suggesting a velocity field of reasonable magnitude. It is also reasonable on the basis of the recording current meter results in Table 5, to assume that this velocity field exists at depth. On this basis, employing a numerical model which computes areal distribution of concentration contours based on the areal velocity field should produce reasonable estimates. The velocity fields at 20 and 40 hr after starting the model are presented in Figures 3 and 4 respectively for a wind data series which is basically from the South and Southeast, with a mean of 5 meters/sec. Strong currents are evident in the Burlington Ship Canal in both figures but in opposite directions, indicative of

the periodicity of flow in the canal. A better description of the periodic mass flow in the Burlington Ship Canal is contained in Section A. In general periods of 5.0, 3.2, 2.4 and 2.0 hr were found to be significant and approximated the estimated theoretical free oscillation periods of 4.9, 3.0, 2.2 and 1.6 hr.

Loadings

The loadings are the driving force for the mass transport equation. The model typically requires that the loadings be defined for every time step or approximately every four minutes. Since neither flow nor concentration can be measured accurately at this time interval, some compromises must be made on the input. If less frequent measurements are available at fixed time intervals, then intermediate time points may be linearly interpolated as needed. At present the concentration of the effluent is difficult to measure on a regular basis and hence average values, constant for all times, must be used.

Ideally it is desirable to have some continuous records of loadings from each source. While these records can be obtained, they were not available for all the sources; consequently the loadings were characterized by obtaining some continuous records supplemented by specific intense surveys and daily loading computations. A loading variation index was determined by dividing the standard deviation by the mean value and expressing the result as a percentage.

Table 3 contains the results for one parameter during two intensive surveys at the major outfalls on the Ottawa Street Slip. During these 7 hour surveys the flows remained reasonably constant and the loading variation index varied from 4 to 15 percent. The results obtained by the operation of a submersible recording chemistry meter in the Ottawa Street Slip (near the surface) from February 2 to 12, 1973, appear in Table 4. Here the loading variation index varied from 10 to 18 percent. Computations based upon the daily loading figures for the major industries and municipalities over a 6 month period are presented in Table 2 (the letters refer to the outfall location on Figures 1 and 2) where the loading variation index varies from 3 to 20 percent. (The variation for the municipal loadings is estimated from the raw sewage data).

It was considered that the loadings to the model could be characterised by a constant equal to the mean value for each discharge then comparing this result with that obtained when the loading was increased by 20 percent. The 20 percent would represent a conservative estimate of one standard deviation for all discharges.

The case where the discharges are kept constant at their mean value is referred to as the "REGULAR CASE". The winds and water levels used are for October 4 and 5, 1972, and are listed in Table 1. Figure 5 shows the 520 umhos/cm contour for the regular case existing boundaries, regular case plus 20% increase in loadings and the regular case for the new boundaries. The complete concentration contouring produced by the model are presented in Figure 14 for the existing harbour geometry and in Figure 15 for the new boundaries. For winds South to Southeast, the new boundaries are approximately equivalent to 20% increase in loadings. However, the measured effects are small as the harbour becomes deep quickly and differentiation between the concentration contours is not very prominent.

One of the water quality problems identified in Hamilton harbour was the low dissolved oxygen levels discussed in the dissolved oxygen trend analysis bulletin. Large regions are below the standard specified in the "Guidelines and Criteria for Water Quality Management in Ontario" (Ontario Ministry of the Environment, 1973). An examination of the daily loading figures for the steel industries indicates that four discharges account for most of the chemical oxygen demand loading. Presently no treatment for oxygen demand exists but if conventional treatment was incorporated it could reduce the loading by approximately 33 percent. It is obviously important to determine whether this reduction would be sufficient to elevate the low dissolved oxygen levels.

The numerical model was developed for conductivity which is primarily a conservative consequently no decay or environmental interaction coefficients were involved in the equations. The equations are not limited to conservatives (see equation 4). However, as there were no experimental evaluations of the coefficients (indeed it is difficult to evaluate some of these coefficients in large lakes) it was not possible to use non-conservatives. The modelling of conductivity presents a conservative estimate of pollutant spread since it represents only dilution while for dissolved oxygen demand other processes (photosynthesis, nitrification, biological demand, aeration, etc.) would further affect the spread. Consequently the model was run reducing the conductivity loadings of the major chemical oxygen demand discharges (letters B, C, G and I in Table 2) by 33 percent. The resulting reduction in the portion of the harbour affected by the reduced loadings is represented in Figure 13. A model run for 66 percent reduction is also presented in Figure 13. The model requires as an initial condition the concentrations at all grid points in the field. This was set, based on field data, at 500 umhos/cm uniformly throughout the harbour assuming the bay to be in a quasi-steady state with waste loadings

approximately equalling the interchange throught the harbour mouth. This same initial condition was used in testing the cases of 33% and 66% reductions. However, if a longer simulation was run on the latter two cases the concentrations throughout the harbour would generally decrease to some new quasi-steady state. This means that the concentration contours for these two cases would in fact contract even closer to the source than is represented in Figure 13.

From Figure 13 it is possible to estimate the percentage reduction in volume of harbour affected by the 33 percent loading reduction for the selected discharges. It is expected that approximately a similar volume of the harbour would show an improved dissolved oxygen level. It is obvious that this technique can only produce an estimate of sorts as the low dissolved oxygen levels are occurring at depth and the model operates on the mean depth values and treats dissolved oxygen as a total conservative. However, it is possible to determine if conventional treatment is likely to improve the dissolved oxygen problem. Another alternative is to examine the effects of artificially destratifying (or depth mixing) which is discussed under stratification. Destratification has the added advantage of oxidising the bottom sediments or accumulations of oxygen demanding products on the bottom.

Bottom Friction

Bottom friction is normally determined in the field or numerically by adjusting the friction factor "n" so that the model velocity corresponds to a measured field velocity. While some area velocity measurements were made, these were not synoptic in sufficient detail to be useful in evaluating "n". Consequently, the sensitivity of the model to bottom roughness was determined by running the model for n=0.015, then changing the n to 0.050 and rerunning the model while holding all other inputs the same. The two values of bottom roughness represent a reasonable range of expected values for Hamilton harbour (Chow, 1959). The 520 umhos/cm contours for the two values of bottom roughness appear in Figure 6.

Dispersion Coefficient

Dispersion coefficients can be determined by conducting dye injection experiments or by numerically determining the dispersion coefficient required to match measured concentration contours of a passive containment. While some limited field data are available on the dispersion coefficients it is not adequate to meet the requirements of the model solution and it was decided to run the model twice, once for high dispersion and once for low dispersion in a similar manner to the bottom roughness runs.

For computational purposes, the dispersion coefficient is related to the magnitude of the winds. The high and low values used represent the range of values found in tidal estuaries. The 520 umhos/cm contours for high and low dispersion coefficients appear in Figure 7.

Stratification

As stated earlier, the two-dimensional form of the model is not well suited to considering stratification. However, it is possible to estimate qualitatively the effects of stratification by assuming that the epilimnion and hypolimnion waters do not mix. As all the major discharges and intakes are in the mean epilimnion, the effect of stratification is to reduce the depth of the receiving water. Consequently, two runs were made for the same input data. The first run uses the bottom contours presented in Figure 1 and assumes no stratification. The second run limits the maximum depth to approximately 5 meters, the mean depth of the epilimnion. The 520 umhos/cm contours for these two cases are presented in Figure 10.

Examining the stratified and non-stratified cases can also be enlightening in the search for ways of improving harbour water quality. The Ministry of the Environment has artificially destratified four small lakes (Ontario Ministry of the Environment, 1972 and Ontario Water Resources Commission, 1971) to improve water quality. This technique brings bottom waters to the surface with air bubbles where they can be aerated by natural processes. It prevents anoxic conditions from occurring in the bottom waters thereby oxidising the bottom sediments and preventing phosphorus from recycling. It has been found effective in limiting algae growth or causing algal succession. pH and alkalinity have also been found instrumental in controlling algal succession via the available CO_2 but mainly in soft water lakes. Obviously the model examination of the stratified and non-stratified cases does not examine the complete mechanism of artificial destratification as it only examines the effect of thoroughly mixing the water column. However, thorough mixing of the water column is a feature common to all destratification experiments so that the model does provide an estimate of the effects of destratification. Section D, Dissolved oxygen trend analysis, indicates that large regions of the harbour have almost anoxic conditions near the bottom. Section B, Nutrient trend analysis, indicates that eutrophic conditions (chlorophyll a >17 ug/l and total phosphorus >40 ug/l similar to the western basin of lake Erie) exist in Hamilton harbour. Consequently it is important to examine destratification as a means of enhancing harbour water quality.

The 1964-5 surveys of the harbour showed the bottom sediments in the Ottawa Street Slip area (location 255) and the deeper waters (location 258 and 254) have 18 and 10 percent loss on ignition (Johnson and Matheson, 1968). While these losses on ignition cannot be directly related to organic content due to the decomposition of iron hydroxides in the test, these regions are characterized by high phosphorus and nitrogen: consequently the sediments are considered to contain high organic content. It is probable that the organic content of the sediments is somewhere between western lake Erie sediments with a loss on ignition of 8 to 9 percent and Bay of Quinte sediments with an 11 to 16 percent (Brydges, 1970). The importance of maintaining aerobic conditions for these enriched sediments (to prevent recycling of nutrients) is obvious. There is probably some merit in even considering the removal of these sediments.

Mass Exchange Through Burlington Ship Canal

One of the important inputs to the model is the time history of the mass exchange in the canal. It is immediately recognised that the exchange is complicated by both the periodic motions in the harbour and varying degrees of stratification within the canal, harbour and lake. The numerical model requires the mean depth integrated velocity and concentration time histories for the canal. As in the case of the loadings, the detailed data required by the model are not available and an alternate approach is used employing the recorded data collected.

Three surveys of water quality concentration and velocity distributions in the canal were conducted during Spring and Summer, 1973. These surveys indicated typical depth variations and variations across the canal. Beyond the boundary layers at the canal walls the variations in velocities and water quality concentrations across the canal were small compared to the depth variations.

Some variations always existed as the boat-collected data were certainly not synoptic. The statistically significant periods, in the 0.5 to 2.4 hour range, in both water quality concentrations and velocities (identified by continuously recording instruments) are likely to affect any boat-conducted survey. In collecting the data for the model it was decided to assume velocities and water quality concentrations were homogeneous across the canal ignoring the boundary layers.

Determining the variations of velocities and water quality concentrations with depth and time obviously requires some form of profiler. This profiler must be operated either continuously or periodically at the required time intervals. While equipment of this type could be built, the time frame of the study did not permit such an activity. Consequently it was decided to operate two recording water quality instruments paired with recording current meters at two fixed locations in the canal on a continuous basis. It was appreciated at the outset that an instrumentation set up like this would not be adequate to define the stratification and mass exchange. However, by positioning the two instruments not too close to the bottom or surface so that each resides predominately in the canal surface and bottom layers, it is possible on some occasions to estimate a mass exchange. It is also possible to estimate the variation with time by using profiling data obtained by conventional sampling methods. Admittedly this approach falls short of the desired instrumentation for the model, however, the operational difficulties encountered in even this simple system are numerous. This instrumentation setup required the simultaneous operation of two digitally recording water quality instruments with pump intakes and two digitally recording current meters over an extended period of time in a canal that is heavily used by shipping and that has periodic water velocities in excess of 80 cm/sec in directions 180 degrees apart. Maintaining the instruments in a calibrated and functional condition was difficult with the result that the percentage of valid data is small and one is forced to synthesize the character of the canal water quality concentrations and then use the measured velocities to obtain the mass flows. The model velocity was simply the mean of the velocities recorded by the two instruments in the canal. Synthesizing the concentrations consisted of using the mean measured concentration then limiting the model rate of change so that it is compatible with the measurements. While the occurrence of simultaneous data from all four instruments is less frequent than desired it does provide valuable information on the relationships between water quality and currents as well as the differences/similarities of the top and bottom layers in the canal particularly in the water quality. The discussion of the recording instrument data is included in the section entitled Harbour Periodicities. A few figures are included in this report from analog dissolved oxygen probes operated in the sampling wells of the chemistry instruments in August which show the complexity of the canal mechanisms:

(a) water quality concentrations can have a different time history than water temperatures (Figure 26).

(b) both water quality and temperature of the bottom layers of the canal can have different time histories (Figure 27) than those in the upper.

Temperature and conductivity depth profiling was carried out on several occasions. Figure 28 shows the depth variation measured during July 11. The two layer system is apparent. It is also apparent that greater separation of the two water chemistry intakes is desirable. However as it is necessary to stay out of the bottom boundary layer and achieve an adequate submergence for protection from small craft and waves the possible separation of the two intakes is limited practically.

The effects of ships in the canal on the mass exchange is significant. Figure 29 shows the depth distribution of dissolved oxygen, conductivity and temperature on July 10. The depth distribution is completely different but does return to the two layer system of Figure 28 shortly after the ship has passed. As the frequency of ships in the canal is low on a 24 hour basis, the effects of ships were ignored.

SURVEY DATA

The 17 sampling locations indicated by a circle and number in the figures were sampled at depths of 0.2, 1.5, 3.0, 4.5, 6.0, 9.0, 12.0, 15.0 and 18.0 meters if possible four times between August and November, 1972. The individual surveys normally required two to three days to complete. During the sampling period the wind climates varied (see Table 6) and consequently the results are not synoptic, particularly when it is known that periodicities of 5.0, 3.2, 2.4 and 2.0 hours are evident in both current and water chemistry records in the harbour. Attempts were made at synthesizing a synoptic (simultaneous) data set from the measured data. The measured depth distribution of specific conductance at each location was nondimensionalized by parameterization. The thermocline was then established at the same depth for all locations, namely at the mean survey depth and the depth distribution reconstructed at each location. Unfortunately this technique was not successful as it was not possible to maintain the same integrated mass in a column of water. The most consistent meteorological conditions and depth stratification existed during the October 4 and 5 survey. These dates were subsequently used for most of the model testing even though the wind speeds of 1.8 to 6.2 m/sec are low. The mean annual wind speeds for 1970, 1971 and 1972 were 7.7, 8.5 and 10.6 m/sec.

Concentration contouring was carried out for the 4 surveys (appreciating that the data is not synoptic) to obtain a qualitative representation of the specific conductance in the harbour. The mean depth values in Figures 19 to 22 and the mean epilimnion values appear in Figures 23 to 25. It is obviously difficult to delineate concentration patterns resulting from specific wind conditions although calms and winds with easterly or westerly components seem to permit the discharged dissolved solids to affect more of the harbour. This is more evident in the epilimnion plots (Figures 23 to 25). However, it is apparent that the concentration configuration is variable and to a large extent some function of wind climate. As expected the mean epilimnion concentration configuration is more variable than the mean depth values.

A twenty-four hour water chemistry survey was conducted at a fixed location at the eastern end of the harbour near the Burlington ship canal on July 10 and 11, 1973. Samples were collected at a depth of 3 meters below the surface and analyzed for temperature, dissolved oxygen, conductivity and pH (Table 7). The winds were generally light 1.8 to 6.7 m/sec and predominately from the west and north during the 24 hour survey (Table 8). With the exception of dissolved oxygen and pH which showed a diurnal variation due to photosynthesis, the variation of temperature and conductivity was small (Index of variability - 5 percent). The small observed variation during consistent wind climates suggests the importance of the wind in the distribution of a contaminant in the harbour as it is known that the principal waste discharges have indices of variation of 4 to 20 percent.

The general shape of the 520 umhos/cm contour determined by the numerical model in Figure 5 for the wind series of October 3, 4 and 5 lies between that determined from the mean depth survey data in Figure 21 and the mean epilimnion data in Figure 25.

A better match with the mean depth survey data in Figure 21 could be obtained by increasing the dispersion coefficient or adjusting the water depths in the model. However, as discussed previously, the results in Figures 19 to 25 are not synoptic, whereas the numerical model results are synoptic for the end of October 5th and adjusting the model results to fit the survey data is not justified. The fact that the model results compare favourably is considered validation that the model is predicting survey results reasonably well and using the model in a qualitative sense is justified. Further justification for using the numerical model is that a completely different pattern of concentration contour is obtained if the wind direction is reversed, which is similar to that observed in Figures 19 to 25 for a variety of wind climates.

DISCUSSION

The preceeding paragraphs on the model testing program have been directed at;

(a) demonstrating that the model is reasonably representative of the harbour processes;

(b) identifying the most important input variables and determining whether these variables can be adequately defined for the model application;

(c) demonstrating that the sensitivity of the model is adequate to assess the water quality changes that are likely to occur if loadings or shoreline geometry are changed or some techniques to improve the harbour water quality are implemented.

Consequently the discussion will address these subjects in the same order. There are, however, two other questions which merit comments. The model testing has been based on conductivity which in itself is not of prime interest for water quality criteria. What is the significance of the conductivity model? And secondly is the two-dimensional form of the model appropriate when it is known that stratification is of primary concern?

The significance of the conductivity is that it is a discharge tracer that can be accurately measured cheaply. It is assumed that other discharged contaminants will react in a similar fashion. The model is then employed in a strictly comparative manner between various cases involving conductivity, thus, it is only necessary that other contaminants react in a similar sense as far as the differences between two cases are concerned. There is no attempt to use the model in a quantitative manner as the data input requirements cannot be appropriately determined. Model verification is presently limited and is qualitative. In this way the use of conductivity as a means of comparing different alternatives seems justified.

The limitations of the two-dimensional model must unfortunately at this time be accepted as it is not possible to properly verify even this simplified model form. The survey results do show that stratification and periodic internal waves are present on most occasions from March to November. It is possible to assume that no mixing of the epilimnion and hypolimnion occurs and to examine the epilimnion as a separate body of water. This provides some estimate of the stratified case as compared to the non-stratified case (Figure 10). While the two cases modelled may be compared it is known that the measured stratification in the harbour presents a much more involved and complicated process than has been assumed for the model. Hence, these comparisons provide only a qualitative estimate of the effects of stratification.

Model Representative of the Harbour Processes

Validating the model requires depth distributions of water quality parameters collected simultaneously at numerous points every half-hour for a period of the order of months. While this is presently technically feasible it was not operationally possible for this study. Continuously recorded velocities, water levels, winds and some chemical concentrations were measured at selected locations and used as inputs to the model. Periodic conventional surveys were also carried out and supplemented by some continuously recorded fixed point data. The model results were compared to the survey data to determine whether the model was producing the expected range of values. Figures 19 to 25 represent the actual water quality survey results. It is possible to state that the model results in Figure 5 lie somewhere between the actual survey results in Figure 21 and 25 which is reassuring.

The velocity magnitudes of the model are reasonably close to the arithmetic mean values determined by recording meters at two different depths (Table 5). Measurable velocities do exist at depth in the harbour with the magnitudes of the same order as the surface velocities. Consequently a two-dimensional model may be expected to depict the velocity field reasonably well. The drogue measurements in Figure 18 compare reasonably well with model predictions.

The currents predicted by the model are similar in magnitude to the statistical mean value obtained from the recording current meters.

Intense sampling of the major industrial outfalls and at several locations in the harbour provide a range of expected variation in water quality over periods of 8 and 24 hrs. The model prediction at these locations produce similar magnitudes of variation for the same time periods. And finally the resulting model predictions for a change in wind direction (Figure 8) are similar to that observed for the different wind climates represented in Figures 23 to 25.

Input Variables

The input variables are defined in equations 1 to 4. These variables were discussed previously and in this section the relative importance of each is discussed. Those variables causing the greatest change in the numerical solution in terms of generating a different concentration contour configuration for the harbour are considered the most important. As most of the input variables cannot be defined in the desired detail, it was necessary to use values which were estimated to represent the processes in Hamilton harbour. The method of selecting the values for the input variables was discussed previously.

Of the input variables tested, the one which affects the shape of the conductivity contours most significantly, is the wind direction (Figure 8). The next most significant factor is stratification. From Figure 10, it is evident that the two-dimensional model is conservative in predicting the effects of the discharges on the harbour water quality, if stratification is present. The stratification case shows that a much greater portion of the harbour is affected for the existing discharges into the epilimnion if the discharged contaminant remains in the epilimnion. Survey results in the Ottawa Street slip, as well as general survey data presented in Figures 19 to 25, show that much of the discharged material does remain near the surface. In a reverse sense, the stratified and non-stratified case presented in Figure 10 provide an indication of the expected improvements that would occur if the area was artificially destratified (Ontario Water Resources Commission, 1971 and Ontario Ministry of the Environment, 1972). In other words it shows that a significantly smaller volume of the harbour would be affected by the existing

discharges if the two layers are mixed so that a uniform concentration exists with depth as was assumed in the model. The depth profiles at location 254 for dissolved oxygen, total phosphorus, free ammonia and iron for August 6, September 6 and October 5 appear in Figures 30, 31 and 32. These figures cover the period of maximum stratification to just before isothermal conditions at the beginning of November. It is observed that the hypolimnetic waters have low dissolved oxygen, total phosphorus and ammonia concentrations compared to the epilimnion. Consequently artificially destratifying the harbour during this period would not only aerate the bottom waters but reduce the nutrient levels in the surface waters and should help reduce phytoplankton productivity. Isopleth plots of dissolved oxygen (Figure 33 and Section D) show the region of low dissolved oxygen near the bottom to grow from mid-August to October. As water temperature variations near the bottom during this period are small, the biological activity rate in the bottom sediments is constant; consequently the changes in dissolved oxygen demand is exerted by the recent phytoplankton die-off.

The model is also sensitive to changes in harbour boundaries. Figure 5 shows that a change of boundary conditions from that of Figure 1 to Figure 2 represents an effect similar to that of increasing the discharges by 20 percent (for the given wind climate). Further alterations of the harbour boundaries for different wind climates would produce other results. Figure 14 shows the effects of the Harbour Commissioners landfilling adjacent to the Burlington Skyway.

The bottom roughness has the least effect on the contaminant distribution in the harbour (Figure 6). Similarly, the periodic flow in the Burlington Ship Canal is a local effect principally affecting the areas adjacent to the canal entrance.

The dispersion coefficient has a reasonable effect on the contaminant distribution (Figure 7). As expected, the high dispersion coefficients disperse the contaminant more quickly and reduces the advection (transport) effect which in turn keeps the 520 umhos/cm level contour closer to the sources (i.e. less of the receiving water is affected by the sources).

Variations in discharge loadings appear in Figures 5 and 13. These figures show that the solution is sensitive to loading changes in a nonlinear manner. Variations of 20 percent in waste discharges cause no change in the distribution of contaminants around the Randle Reef (near discharges B and C and intake A), whereas there is measurable degradation of water quality in the southeast portion of the harbour for the loading change.

In summary the model is sensitive to wind climate, stratification, harbour boundaries, dispersion coefficients and loading changes and appears adequate to examine the effects of filling, treatment and other possible water quality corrective techniques.

Model Sensitivity

One wishes to use the model to determine the expected water quality after the shoreline has been changed, discharges relocated or changed and techniques for improving water quality, (e.g. induced circulation between lake and harbour, artificial destratification etc.) have been initiated. Predicting always implies an associated probability of occurrence or a degree of risk; consequently an effort must be made to determine this probability or at least a range of values for the probability. The probability of occurrence cannot be easily determined here as it was not possible to validate the model in a numerical sense. Instead the model was validated qualitatively and employed qualitatively (comparatively). However, even a comparative application requires some definition of what is a significant difference. Unfortunately the lack of a numerical validation forces one to accept a qualitative definition of significance based on qualitative test. Figures 5, 6, 7, 8, 10 and 13 show the sensitivity of the model solution to the variation of one input variable at a time between its expected extreme values in Hamilton harbour. These input variables are the only variables in the model equations, consequently it can be stated that any difference corresponding in magnitude to the sensitivity tests of the input variables is significant.

The proposed harbour filling (Figure 2) with the existing discharges has approximately the same effect as a 20 percent increase in conductivity loadings (Figure 5). The water quality degradation is particularly evident in the southeast portion of the harbour and it is not simply linearly dependent on volume reductions. As the 20 percent increase in loadings represents at least one standard deviation for all discharge, this condition will be exceeded about 16 percent of the time on a probability basis for the existing discharges. Figure 14 shows the changes in water quality (conductivity) that have occurred as a result of the Harbour Commissioners landfilling adjacent to the Burlington Skyway. The 520 umhos/cm level affects approximately 15 percent more surface area of the harbour water as a result of the Harbour Commissioners filling.

The proposed industrial land filling represents a water volume reduction of approximately 5 percent of the total harbour volume. Most of this filling is in the immediate vicinity of the major discharges and it is in the vicinity of these discharges that significant changes of water quality concentrations are detectable. Other than the southeast region of the harbour, there is little detectable change in water quality due to filling e.g. the Randle Reef region (near discharges B and C and intake A) is little affected by the filling (Figures 5 and 14). The extent of the effect on local water quality due to filling is likely to vary with wind conditions and the water quality parameter modelled. Consequently, the 20 percent loading figure is probably not representative of all conditions. As the model is expensive to run, it is not practical to examine all possibilities. In the present application, the model does show there is an effect on water quality due to filling. This effect is significant considering the accuracies in determining the necessary input variables.

Water quality changes resulting from a 20 percent increase in loadings for all discharges (Figure 5), a 33 and 66 percent reduction in selected discharges (Figure 13 and Tables 1 and 9), pumping harbour water directly to the lake which increases the flow of lakewater into the harbour (Figure 11) and artificially destratifying the harbour (Figure 10) were examined using the numerical model. The purpose of these runs was to determine which methods produced the greatest change in the harbour water quality. Obviously there are many possible alternatives and combinations of alternatives which can be examined. The ones examined here are some of the more obvious approaches which can at least then be qualitatively compared.

Of the alternatives examined, increasing the lake-harbour exchanges by pumping at an arbitrarily selected site, a volume of water equivalent to the industrial recirculated volume directly from the harbour to the lake was the least effective in enhancing the harbour water quality. The most effective alternatives were, in order:

1. artificial destratification
2. 66 percent selective loading reductions
3. universal 20 percent loading reductions
4. 33 percent selective loading reductions

(The 20 percent would include a standard deviation for all discharges while the 33 percent could be achieved by conventional treatment on the major COD discharges.) These results suggest that investigations into the enhancement of the water quality should be directed at destratification and loading reductions of the order of 30 percent or greater.

In the section discussing loadings, it was indicated that it is possible to estimate the effects of reducing COD loadings from the major discharges using the conductivity model in a qualitative manner. Figure 13 shows the resulting 520 umhos/cm contour for a 33 and 66 percent reduction in loadings of the major COD discharges. For the regular case a harbour volume of 16.5×10^6 cubic meters have conductivities in excess of 520 umhos/cm while only 11.5×10^6 and 4.7×10^6 cubic meters have conductivities in excess of 520 umhos/cm for the 33 and 66 percent loading reductions. This means that 5.0×10^6 and 11.8×10^6 cubic meters of harbour water have enhanced water quality. On a percentage basis the loading reductions have approximately the same direct percentage enhancement of harbour water quality. The enhancement resulting from the 66 percent loading reduction would improve approximately 10 percent of the volume of water affected by low dissolved oxygen values.

CONCLUSIONS

A numerical model capable of determining the water quality changes caused by changes in the harbour geometry, water withdrawals and waste loadings for varying meteorological conditions was developed. This model is two-dimensional and time variant using measured input variables (water chemistry, currents, wind and water level recorders). The model predictions were tested to determine their sensitivity to the various input variables; then the model solutions were compared to conventional grab sampling surveys. As it was not possible to synthesize a synoptic data set, these comparisons were qualitative.

The numerical model showed that the proposed industrial land filling (approximately 5 percent of the harbour volume) caused a water quality degradation in the harbour waters adjacent to the filling for one wind climate examined. However only areas immediately adjacent to the new outfall locations deteriorated in excess of the Ministry's objective of no more than a 33 percent increase in dissolved solids. This degradation is approximately equivalent to the effect of a 20 percent increase in existing mean loadings. Similarly the Hamilton Harbour Commissioners landfilling along the Burlington Skyway causes local water quality degradation affecting 15 percent more of the harbour area.

Of the methods examined for water quality enhancement, the best results are realized by reducing the loadings by 66 percent and destratifying the harbour or aerating the hypolimnion. Artificially destratifying the harbour will in addition to aerating the bottom waters reduce the nutrient levels in the surface waters reducing algal fertilization. The bottom sediments are also exerting a large oxygen demand on the harbour waters which suggests that selective removal of some of the sediments should be considered in addition to aerating and controlling algal growths. Artificially inducing circulation between the harbour and the lake was less effective in enhancing water quality in the case examined. The number of cases examined in this study were limited. Obviously many possible combinations of alternatives exist for the enhancement of water quality. There are also many different wind climates. The feasible alternatives should be identified and the numerical model applied for the wind climates of interest to determine which alternatives are the most effective in enhancing harbour water quality.

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TABLE 1

HOURLY PHYSICAL DATA AT HAMILTON HARBOUR

OCTOBER 3/72 - (DIRECTIONS COMING FROM)

TIME	CURRENTS AT BURLINGTON CANAL		WATER LEVELS AT BURLINGTON CANAL	WINDS AT HAMILTON	
Hrs.	cm/sec	degrees	Meters	m/sec	degrees
0000	1.5	157	78.39	0	0
0100	4.2	78	78.39	0	0
0200	3.9	169	78.37	.89	225
0300	7.6	154	78.37	0	0
0400	2.5	198	78.37	0	0
0500	4.7	211	78.38	0	0
0600	6.9	183	78.37	0	0
0700	5.7	118	78.37	.89	180
0800	3.7	96	78.38	1.78	180
0900	3.4	253	78.38	3.57	180
1000	1.3	68	78.38	3.57	180
1100	5.6	56	78.39	4.91	225
1200	3.1	54	78.40	6.25	225
1300	9.5	50	78.39	5.81	225
1400	7.9	194	78.39	5.36	180
1500	2.6	193	78.40	4.47	180
1600	3.7	53	78.38	2.68	180
1700	7.2	254	78.38	2.23	45
1800	5.3	64	78.37	3.12	45
1900	14.3	218	78.38	2.68	45
2000	8.3	159	78.39	3.12	45
2100	7.1	120	78.39	3.12	45
2200	5.5	243	78.38	2.68	45
2300	7.0	123	78.39	3.12	135

TABLE 1 (Cont'd)

HOURLY PHYSICAL DATA HAMILTON HARBOUR

OCTOBER 4/72 - (DIRECTIONS COMING FROM)

TIME	CURRENTS AT BURLINGTON CANAL		WATER LEVELS AT BURLINGTON CANAL	WINDS AT HAMILTON	
Hrs.	cm/sec	degrees	Meters	m/sec	degrees
0000	3.1	210	78.40	3.12	135
0100	4.0	252	78.38	2.68	180
0200	5.6	144	78.37	2.23	135
0300	3.9	99	78.41	3.57	135
0400	10.3	248	78.38	3.57	135
0500	5.5	251	78.38	3.12	135
0600	18.6	75	78.37	3.57	180
0700	19.5	247	78.38	3.57	180
0800	11.2	211	78.39	3.12	135
0900	7.8	42	78.40	4.02	135
1000	7.1	72	78.40	3.12	180
1100	7.1	57	78.40	2.68	180
1200	.7	163	78.40	3.57	45
1300	.3	97	78.42	3.57	135
1400	4.9	213	78.41	4.02	45
1500	7.6	84	78.40	4.02	45
1600	5.7	128	78.39	4.91	45
1700	10.2	250	78.40	3.57	45
1800	5.9	222	78.39	3.12	45
1900	3.5	106	78.38	2.68	45
2000	2.9	158	78.38	3.57	90
2100	5.7	261	78.39	4.91	135
2200	4.8	60	78.41	4.47	180
2300	2.9	174	78.41	3.12	135

TABLE 1 (Cont'd)

HOURLY PHYSICAL DATA HAMILTON HARBOUR

OCTOBER 5/72 - (DIRECTIONS COMING FROM)

TIME	CURRENTS AT BURLINGTON CANAL		WATER LEVELS AT BURLINGTON CANAL	WINDS AT HAMILTON	
Hrs.	cm/sec	degrees	Meters	m/sec	degrees
0000	4.7	104	78.41	3.12	135
0100	12.4	91	78.41	4.02	180
0200	7.7	246	78.39	2.68	45
0300	7.8	149	78.40	1.78	45
0400	3.9	49	78.39	1.78	90
0500	10.6	210	78.37	1.34	90
0600	6.5	275	78.37	1.78	180
0700	3.4	218	78.37	2.23	135
0800	7.0	253	78.39	3.57	135
0900	6.7	225	78.39	4.02	180
1000	8.2	56	78.41	4.47	180
1100	8.0	192	78.39	3.57	135
1200	5.7	205	78.39	5.36	135
1300	7.7	122	78.39	5.36	180
1400	3.8	201	78.40	6.25	180
1500	2.5	95	78.38	3.57	180
1600	10.5	61	78.39	2.68	180
1700	5.4	210	78.37	4.91	45
1800	7.3	194	78.36	3.57	45
1900	4.3	256	78.37	4.02	45
2000	8.3	253	78.38	4.02	45
2100	3.7	217	78.38	3.57	45
2200	8.4	39	78.38	3.12	45
2300	8.5	89	78.37	2.23	90

TABLE 2

Map I.D.	Outfall Intake	MODEL Flow x 10^3 (m^3/day)	MODEL Conduct. (μmho/cm)	MEASURED Flow x 10^3 (m^3/day)	MEASURED Conduct. (μmho/cm)	DISSOLVED SOLIDS LOADING (kg/day) Mean x 10^3	DISSOLVED SOLIDS LOADING (kg/day) Standard Deviation x 10^3	DISSOLVED SOLIDS LOADING (kg/day) Standard Deviation ÷ Mean (%)
A	Stelco Intake #2	- 1349[1.]	0	- 1330	368	- 488	43.9	9.0
B	Stelco S. Open Cut Sewer	248	769	245	785	125	5.3	4.2
C	Stelco N. Trunk Sewer	251	658	246	677	108	4.7	4.4
D	Stelco Intake #1	- 205	0	- 202	623	- 82	13.8	16.9
E	Stelco #3 Open Hearth Sewer	212	626	209	642	87	7.9	9.0
F	Stelco 148" Plate Mill	50	621	50	637	20	1.9	9.6
G	Ottawa St. Slip[2.]	1299	597	931	830	501	16.0	3.2
H	Dofasco raw water intake	- 797	0	- 787	541	- 276	14.5	5.2
I	Dofasco:[3.]	275	656	271	671	118	12.3	10.4
J	Stelco: #2 Rod Mill Parkdale Works	30	469	46	319	10	0.65	6.9
K	Hamilton WPCP	236	742	233	756	114	22.8	20.0
L	Skyway WPCP	-	-	36	749	17	3.5	20 (est)
M	Dundas WPCP	9	712	9	739	4	0.9	20 (est)

1. Negative flows are intakes

2. Stelco (E. side lagoon, HCL regen & cold mill, not strip mill, heavy gauge shear line), Dofasco (lagoon Ottawa St. sewer), C.I.L. (total plant less service water intake)

3. Dofasco (coke oven by products, boiler house discharge, silicon steel)

TABLE 3

MAJOR INDUSTRIAL DISCHARGES
OTTAWA STREET SLIP
HOURLY VARIATION
SPECIFIC CONDUCTANCE - umhos/cm

	DOFASCO LAGOON	OTTAWA SEWER	STELCO EAST SIDE
JAN. 4, 1973.			
10:00 a.m.	676	569	613
11:30 a.m.	629	584	538
1:00 p.m.	600	569	538
2:30 p.m.	645	569	552
4:00 p.m.	629	505	538
5:30 p.m.	615	505	538
mean	632.3	550.2	552.8
std. dev.	26.2	33.5	30.0
Feb. 6, 1973.			
9:30 a.m.	567	553	430
11:00 a.m.	584	491	491
1:00 p.m.	538	538	491
2:30 p.m.	415	553	505
4:00 p.m.	631	505	462
mean	547.	528.	475.8
std. dev.	81.1	28.5	30.

TABLE 4

RECORDING CHEMISTRY METER

OTTAWA STREET SLIP

FEBRUARY 2 TO 12 AT HALF HOUR INTERVALS

(480 Readings)

	Temperature C	Dissolved Oxygen - mg/l	Turbidity SJU
Mean	10.4	8.6	30.
St. dev.	1.6	0.7	5.5
St. dev/mean	0.16	0.10	0.18

TABLE 5

Recording Current Meters' Summary

Operated at 43° 17' 28" N 79° 49' 56" W*
December 14, 1972 to February 3, 1973

Period	Dec. 1972		Jan. 1973	
Location	16.1 m from bottom	6.1 m from bottom	16.1 m from bottom	6.1 m from bottom
Resultant Speed (cm/sec)	1.82	0.42	3.01	1.14
Direction in degrees (0° North) Going to	353	349	344	5
Mean Speed (cm/sec)	2.73	1.76	4.05	2.42
Maximum Speed (cm/sec)	35.17	9.4	35.77	14.78
Peristence	0.67	0.24	0.76	0.47
Total No. of Reading	4896	4971	8929	8929
Interval of Readings (minutes)	5	5	5	5
Period of Zero Velocity (% of recording period)	6.3	1.7	2.8	7.2
Period of Low Velocity (<2.00 cm/sec)	41	68	25	48

* Total water depth 22.8 m

TABLE 6

WIND RECORD SUMMARY - DURING SURVEYS

DATE	TIME	DIRECTION (deg)	SPEED (m/sec)
Aug. 5	1200 to 2400	SW	1.3 to 4.4
Aug. 6	0001 to 0800	W,SW	1.3 to 2.7
	0801 to 1500	S	2.7 to 3.1
	1501 to 2400	E,SE	1.3 to 3.6
Aug. 7	0001 to 0500	S,SW	1.8 to 4.4
	0600 to 1200	E,SE	1.3 to 2.7
Sept. 5	0001 to 2400	S,SW	1.7 to 6.7
Sept. 6	0001 to 0600	W	1.3 to 3.1
	0601 to 0900	CALM	
	0901 to 1100	SE	1.7
	1101 to 2400	S,SW	1.7 to 3.6
Sept. 7	0001 to 2400	S.SW	2.2 to 9.0
Sept. 8	0001 to 0300	SW	1.7 to 2.2
	0301 to 0600	CALM	
	0601 to 1600	N.NE	.9 to 3.6
	1601 to 1900	VARIABLE, CALM	
	1901 to 2400	N	3.6 to 4.5
OCT. 3	0001 to 0700	CALM	
	0701 to 1700	S,SW	.9 to 6.3
	1701 to 2400	NE	2.2 to 3.1
Oct. 4	0001 to 1200	S,SE	2.2 to 4.0
	1201 to 2000	NE	3.1 to 5.0
	2001 to 2400	S,SE	3.1 to 5.0
Oct. 5	0001 to 0200	S,SE	3.1 to 4.0
	0201 to 0400	NE	1.8 to 2.7
	0401 to 1700	S,SE	1.4 to 6.3
	1701 to 2400	NE	2.2 to 4.0
OCT. 31	0001 to 0800	N,NE	1.3 to 2.7
	0801 to 2400	E,NE	1.8 to 7.6
Nov. 1	0001 to 2400	E,NE	2.2 to 7.2

TABLE 7

24 HOUR HAMILTON HARBOUR WATER CHEMISTRY
(GRAB SAMPLING 10 AND 11 JULY 1973)

TIME	TEMP. DEGREES CENT.	DISSOLVED OXYGEN mg/l	COND. AT 25 DEGREES umhos/cm	pH.
1445	25.3	7.8	580	8.2
1645	24.8	9.0	622	8.5
1845	24.6	9.0	592	8.2
2045	24.3	8.9	558	7.7
2255	23.0	1.5*	610	7.5
0055	24.0	6.3	594	7.4
0305	23.7	6.8	635	7.6
0500	24.2	6.1	645	7.5
0705	23.0	6.2	687	7.5
0940	22.0	5.9	580	7.7
1110	22.0	6.5	635	8.0
1320	21.8	7.6	610	8.1
Mean	23.5	7.3	612.	7.8
St. Dev.	1.2	1.2	35.	.4
Index of Variation	4%	16%	5%	4%

* Not included in mean or st. dev.

TABLE 8

WIND AND WATER LEVEL CLIMATE
10 AND 11 JULY 1973

		WIND		WATER
		Speed M/Sec.	Dir.	LEVELS M
July 10	0900	3.1	W	75.447
	1100	1.8	W	.426
	1300	4.0	W	.456
	1500	4.9	W	.456
	1700	4.9	NW	.417
	1900	4.0	N	.447
	2100	3.6	NW	.417
	2300	2.7	NW	.395
July 11	0100	2.2	NW	.426
	0300	2.2	NW	.408
	0500	2.7	N	.426
	0700	4.0	N	.408
	0900	6.7	N	.417
	1100	5.8	N	.417
	1300	5.4	NW	.426
	1500	6.3	NW	.426

TABLE 9

PRINCIPAL CHEMICAL OXYGEN DEMAND (COD) LOADINGS

LOCATION	MAP REFERENCE FIG. 1	LOAD $\times 10^3$ kg/day
Stelco South Open Cut Sewer	B	10.1
Stelco North Trunk Sewer	C	9.9
Ottawa Street Slip	G	55.5
Dofasco	I	18.6

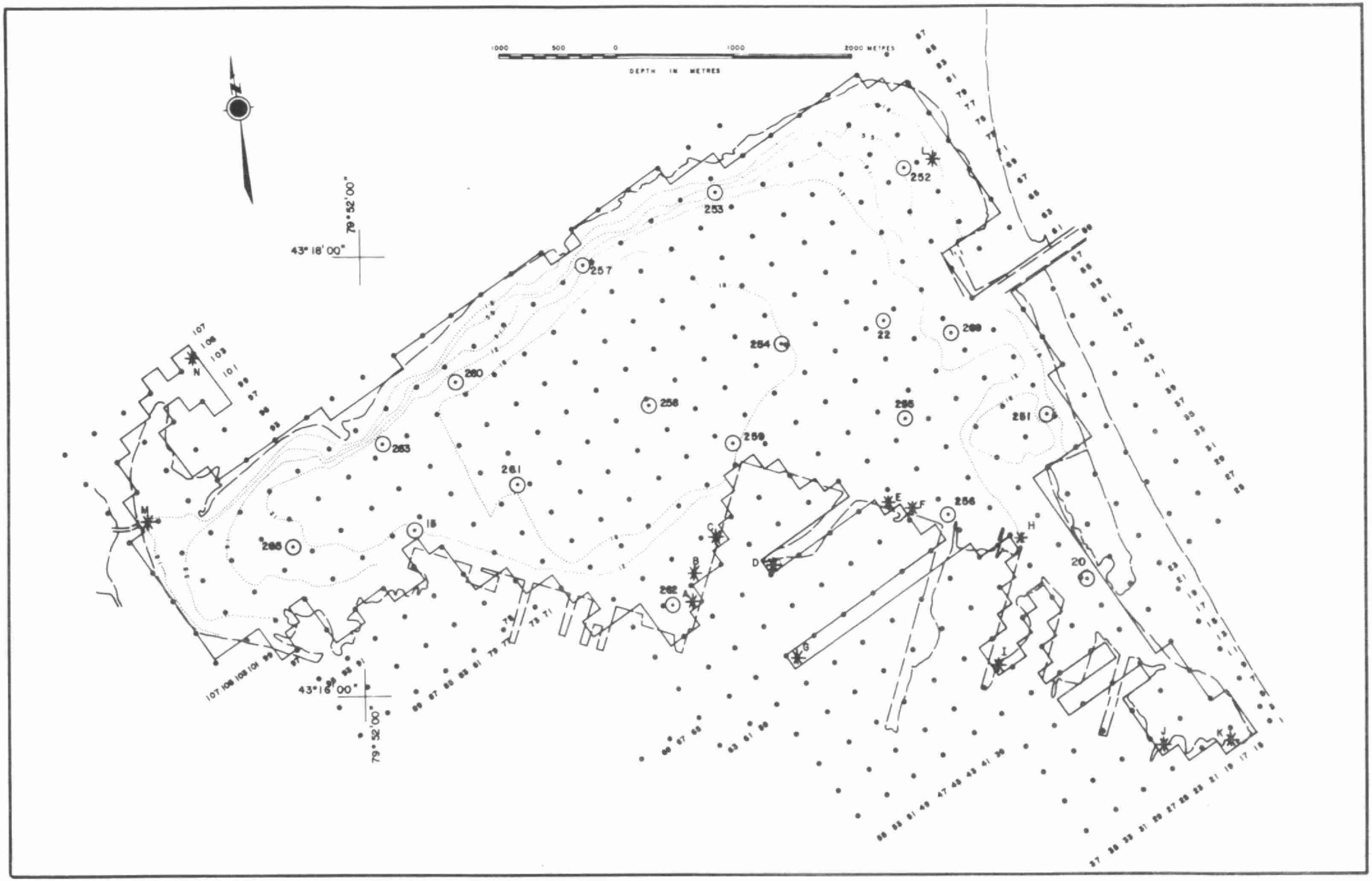


FIGURE I : MODEL NUMERICAL GRID WITH 1972 SHORELINE

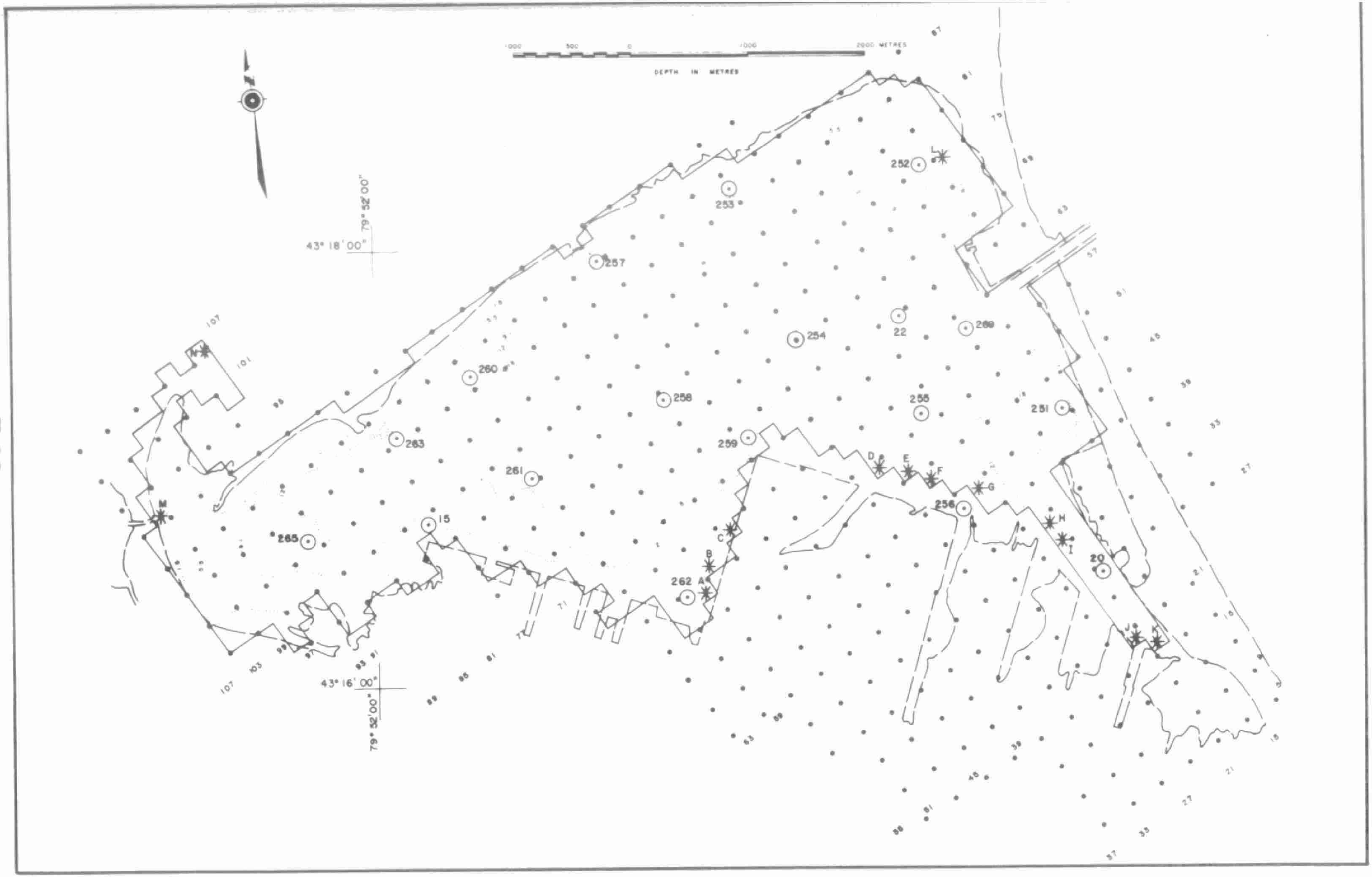


FIGURE 2 : MODEL NUMERICAL GRID WITH PROPOSED SHORELINE

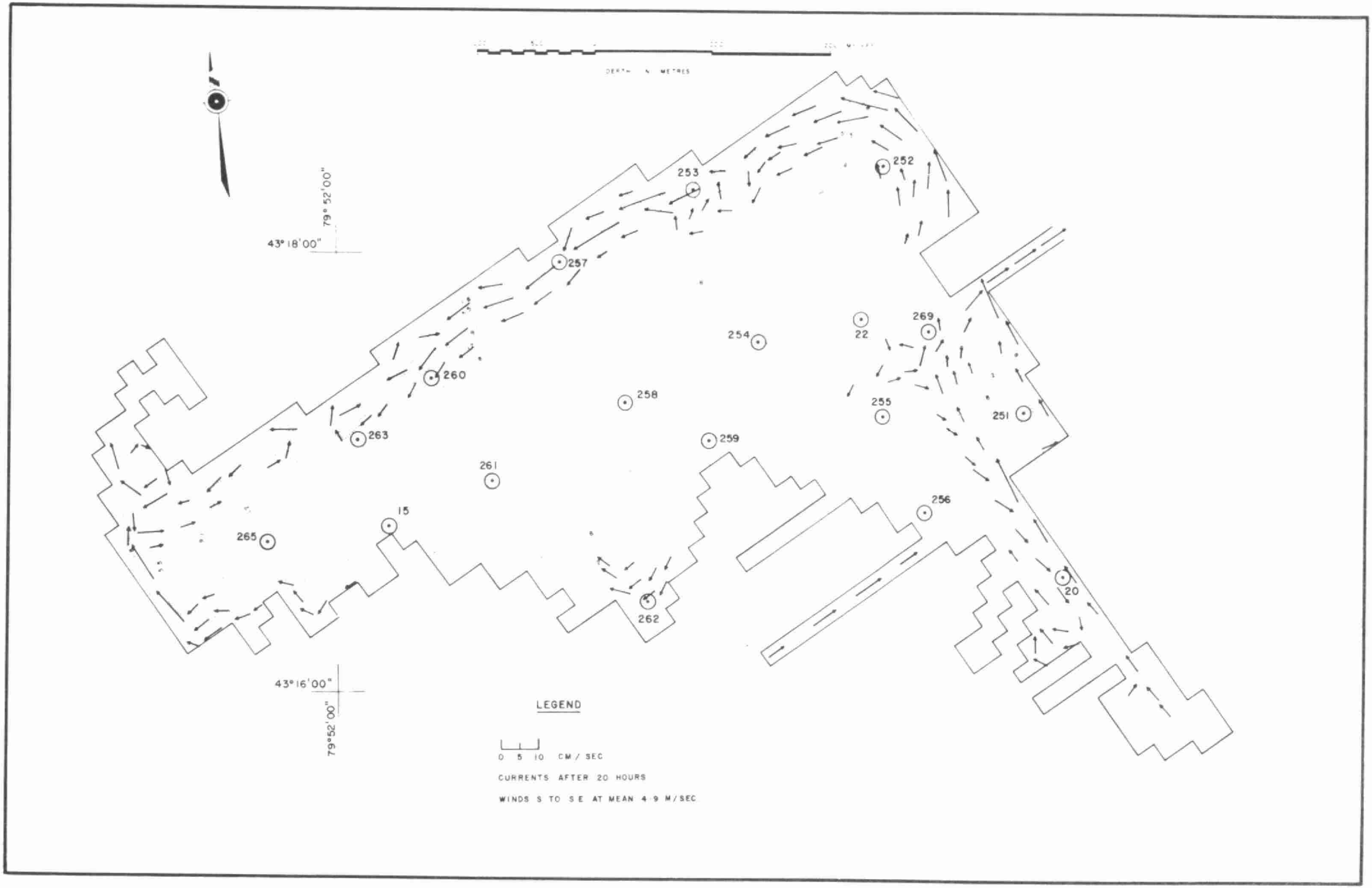


FIGURE 3 : MODEL PREDICTIONS OF CURRENT FIELD OCTOBER 4, 1972

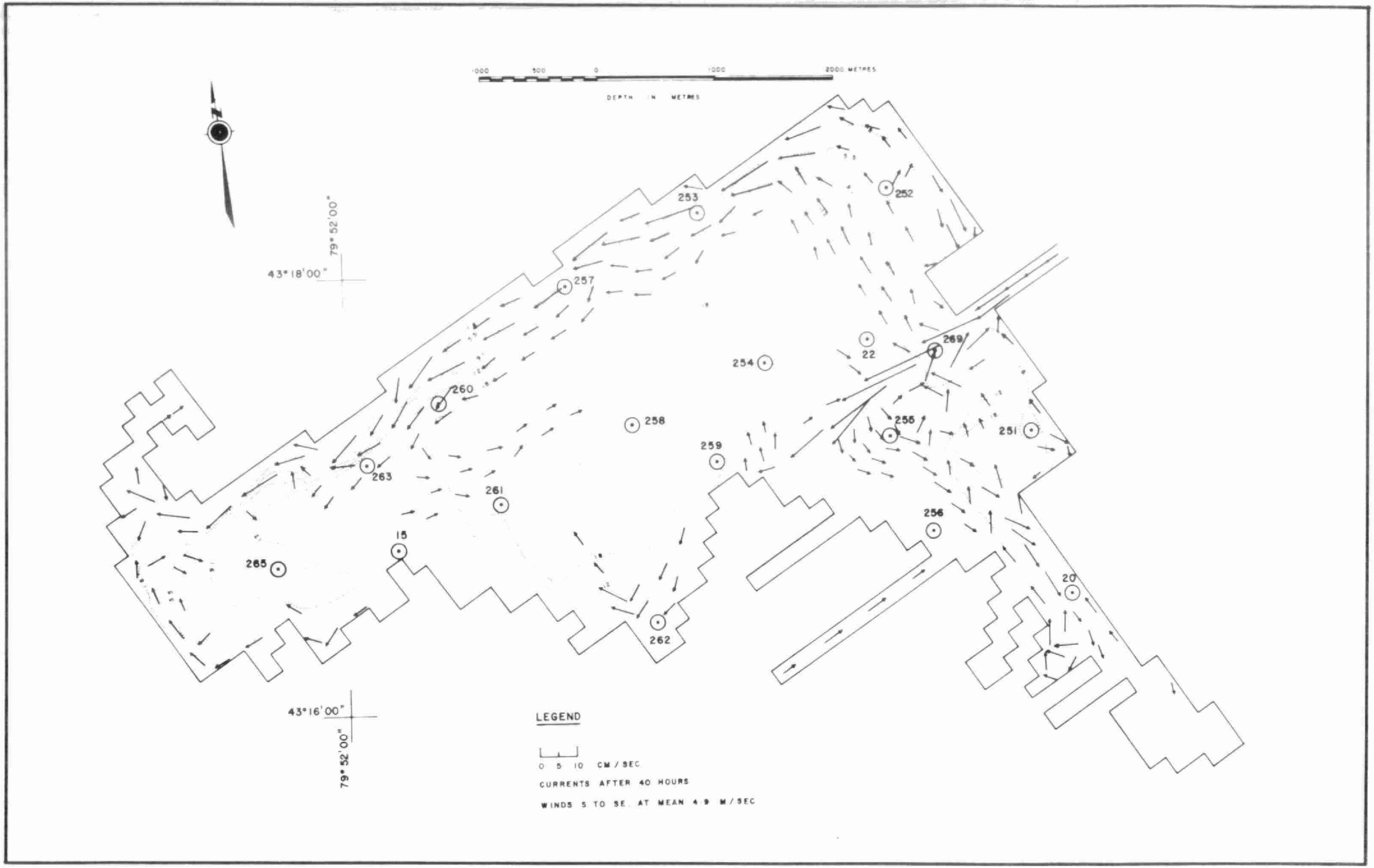


FIGURE 4 : MODEL PREDICTIONS OF CURRENT FIELD OCTOBER 5, 1972

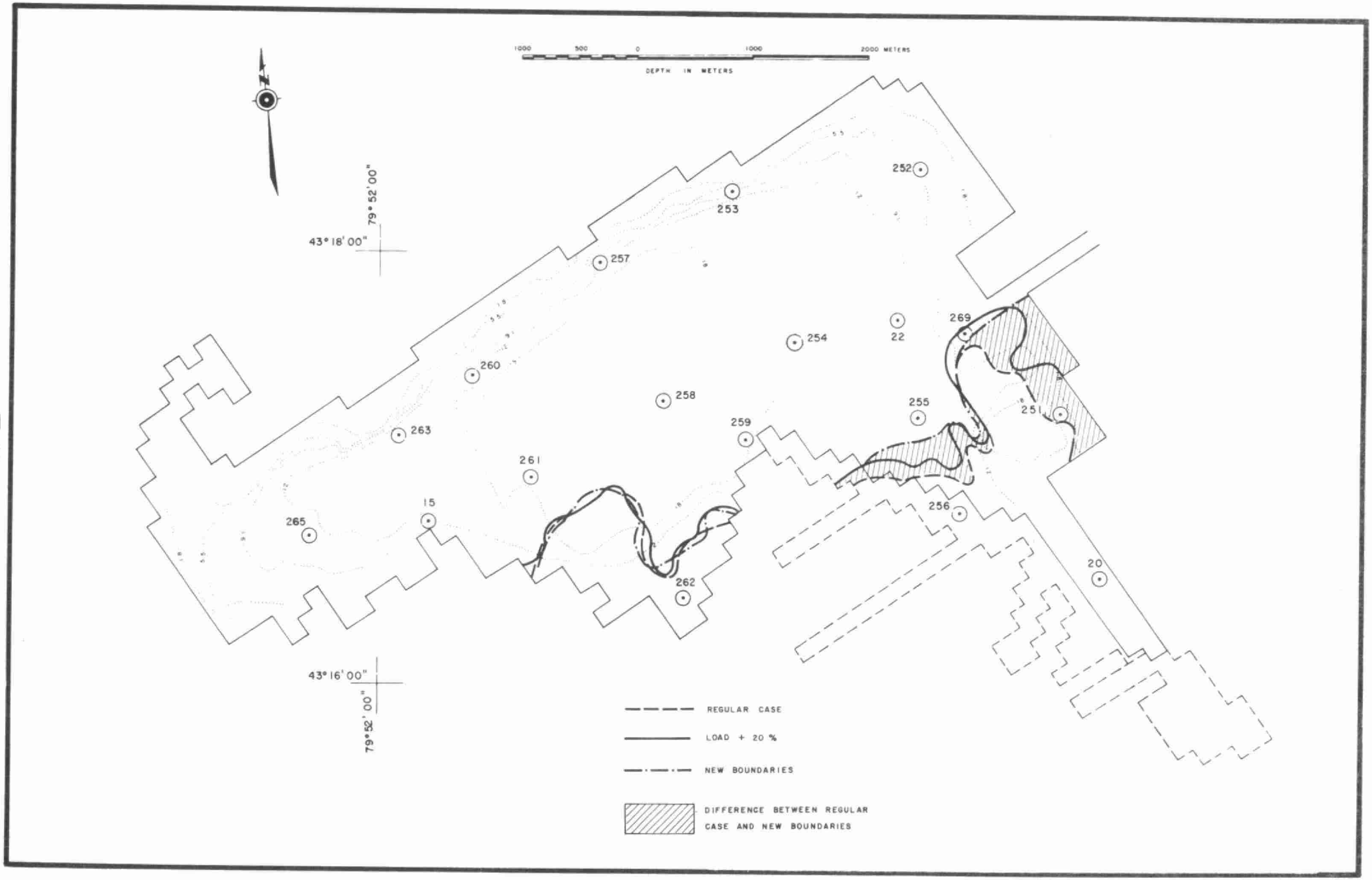


FIGURE 5 : MODEL PREDICTIONS OF 520 μmhos/cm CONTOUR

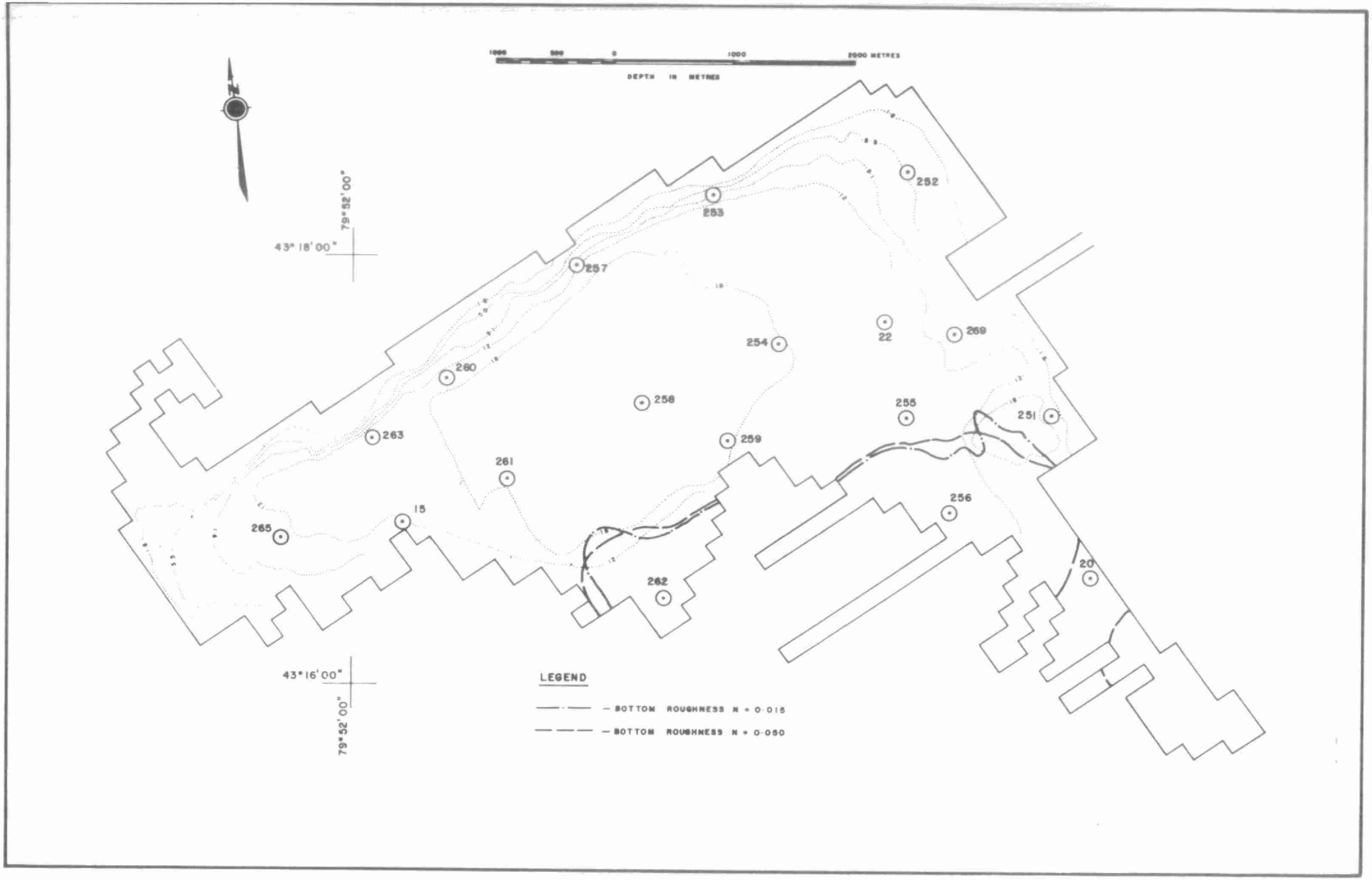


FIGURE 6 : SENSITIVITY OF MODEL PREDICTIONS TO BOTTOM ROUGHNESS

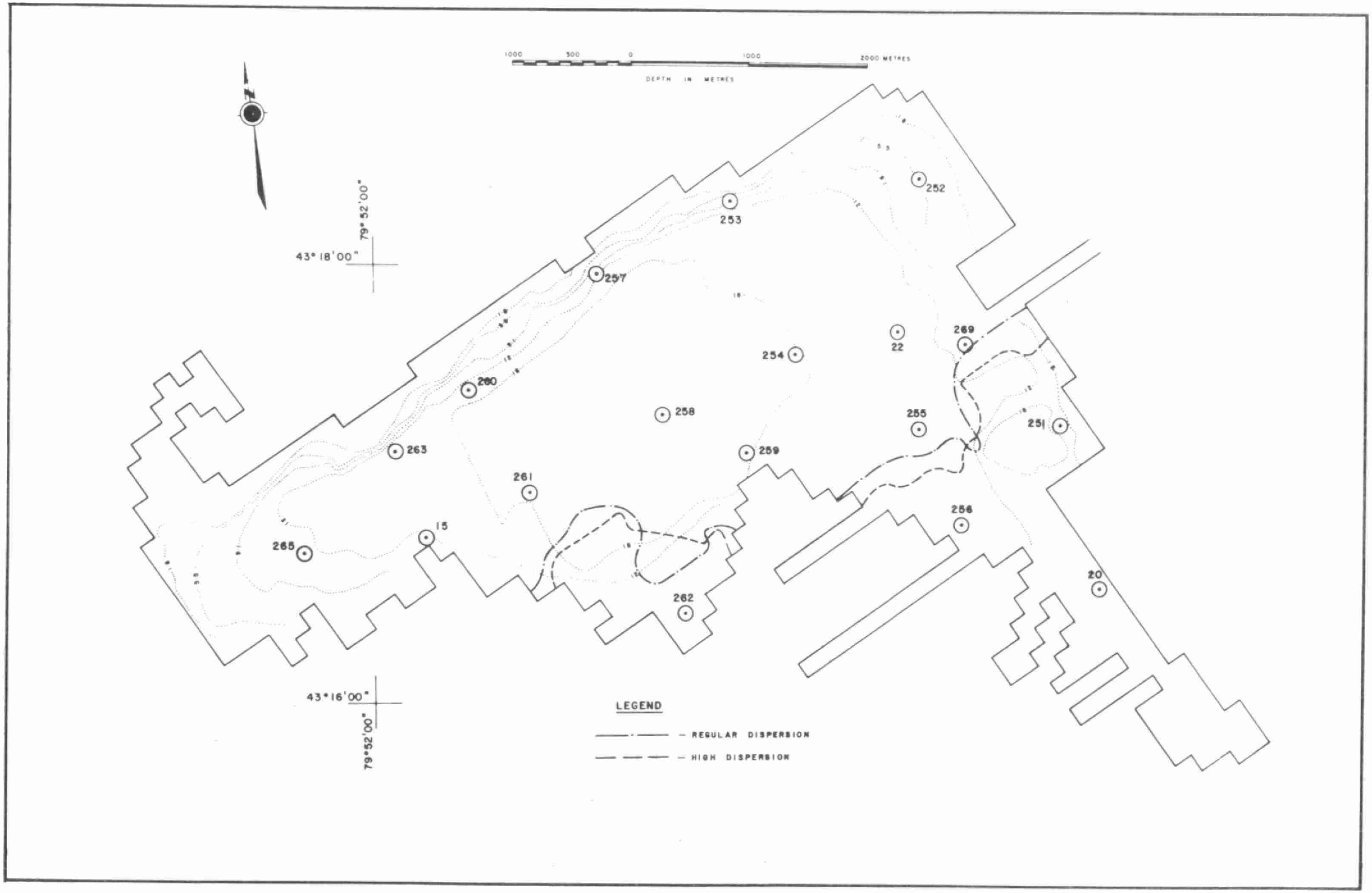


FIGURE 7 : SENSITIVITY OF MODEL PREDICTIONS TO DISPERSION

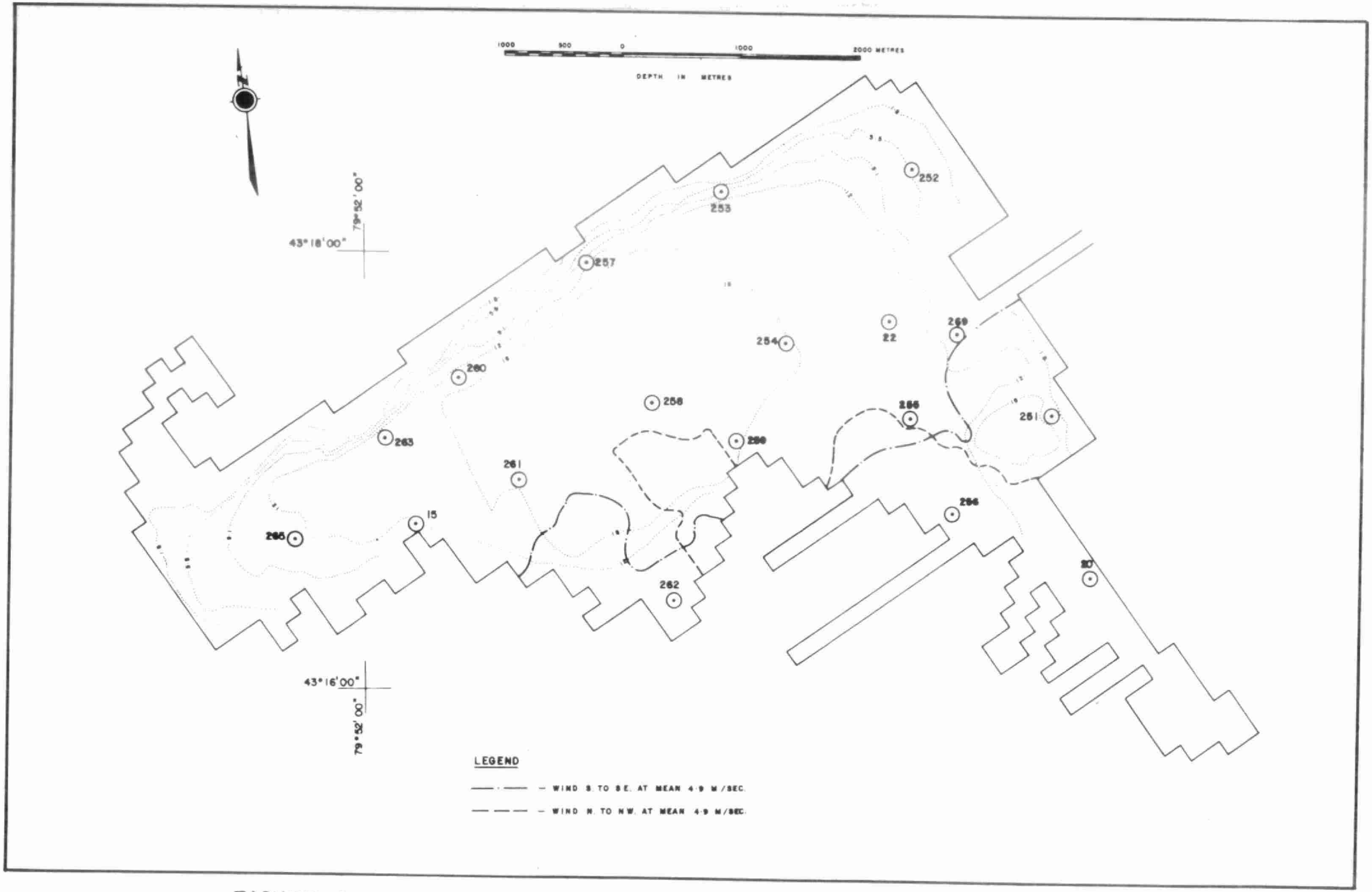


FIGURE 8 : SENSITIVITY OF MODEL PREDICTIONS TO WIND DIRECTION

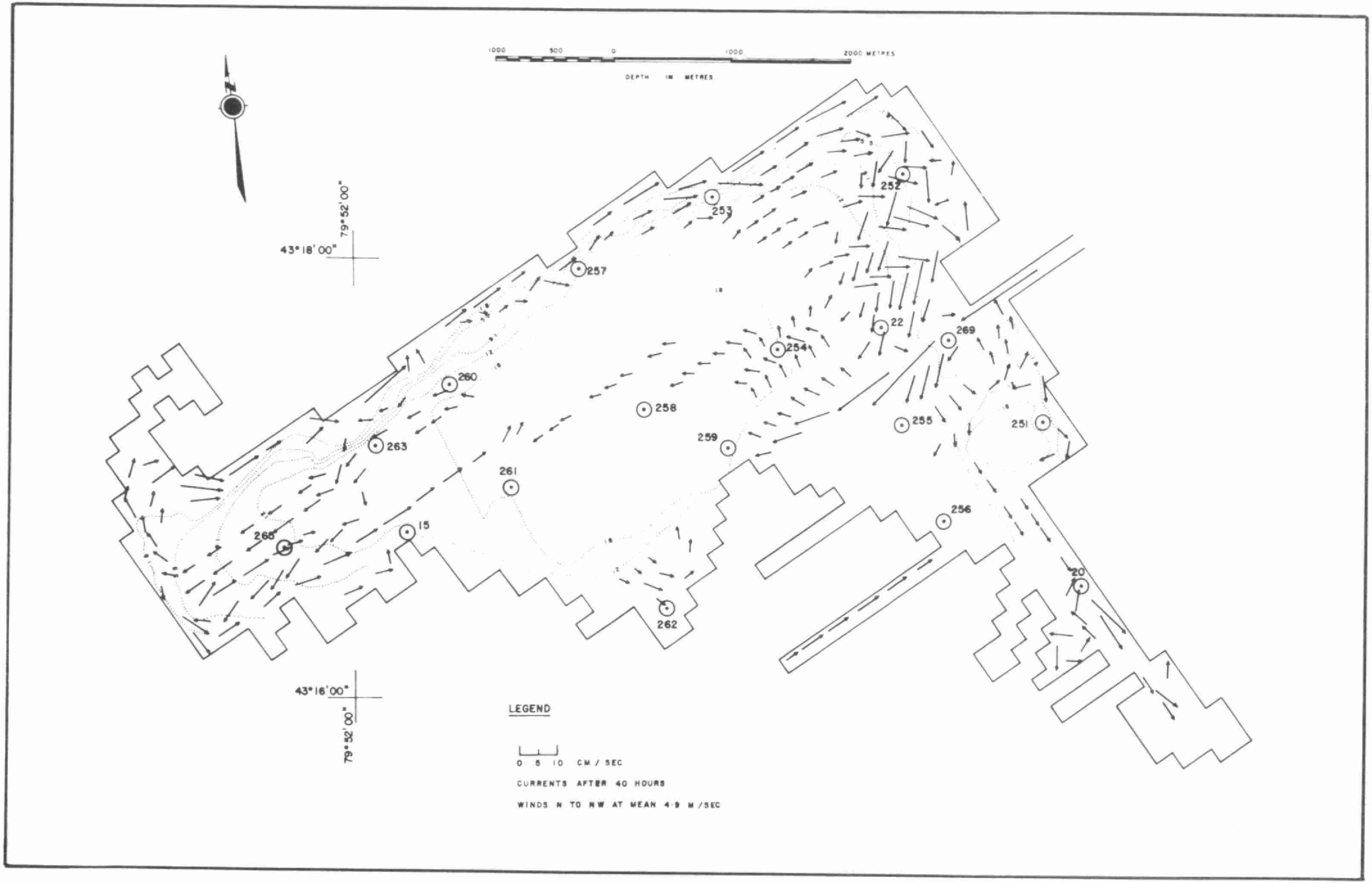


FIGURE 9 : MODEL CURRENT FIELD FOR A WIND DIRECTION REVERSAL

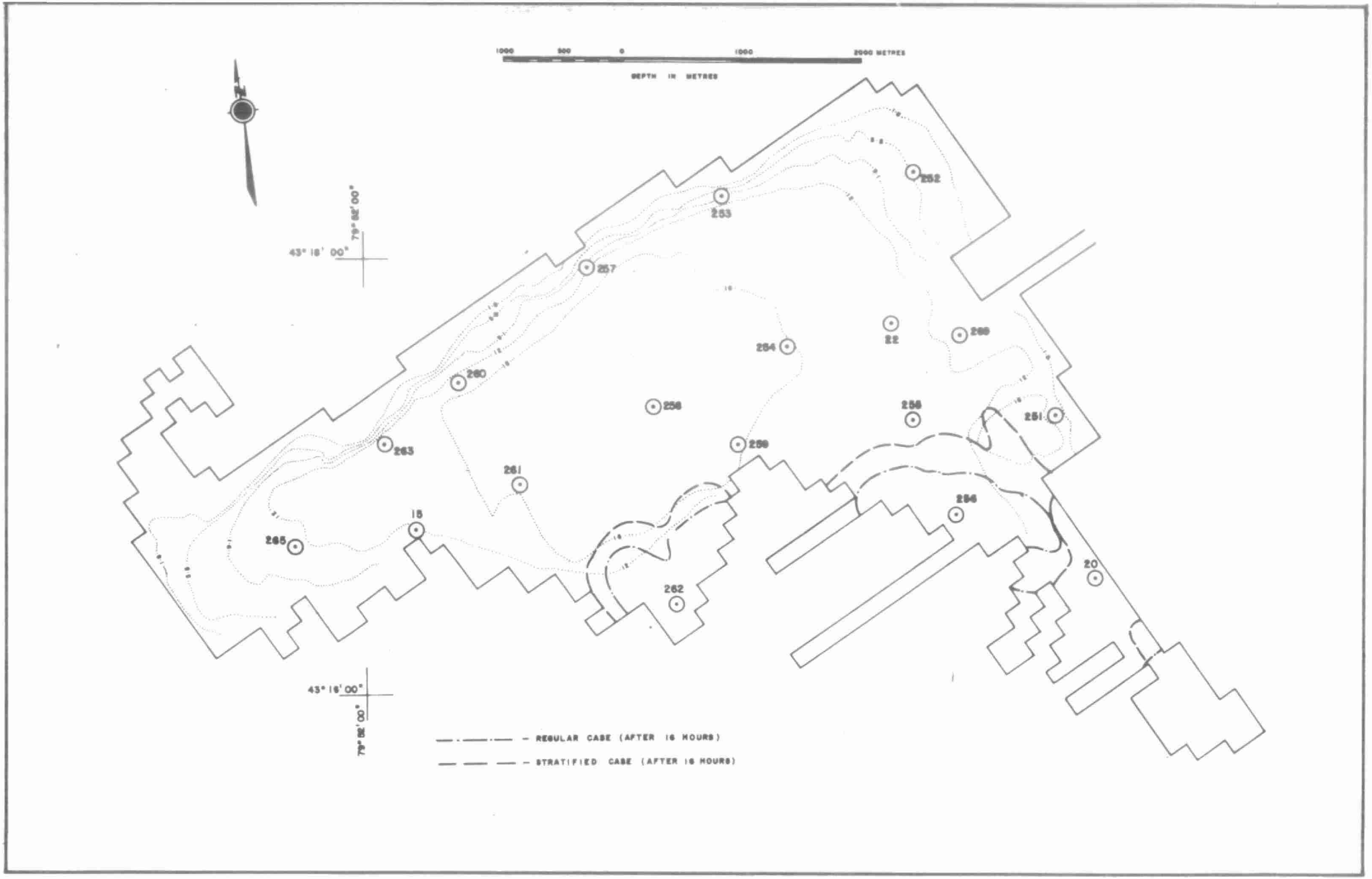


FIGURE 10: SENSITIVITY OF MODEL PREDICTIONS TO EPILIMNION CONSIDERATIONS

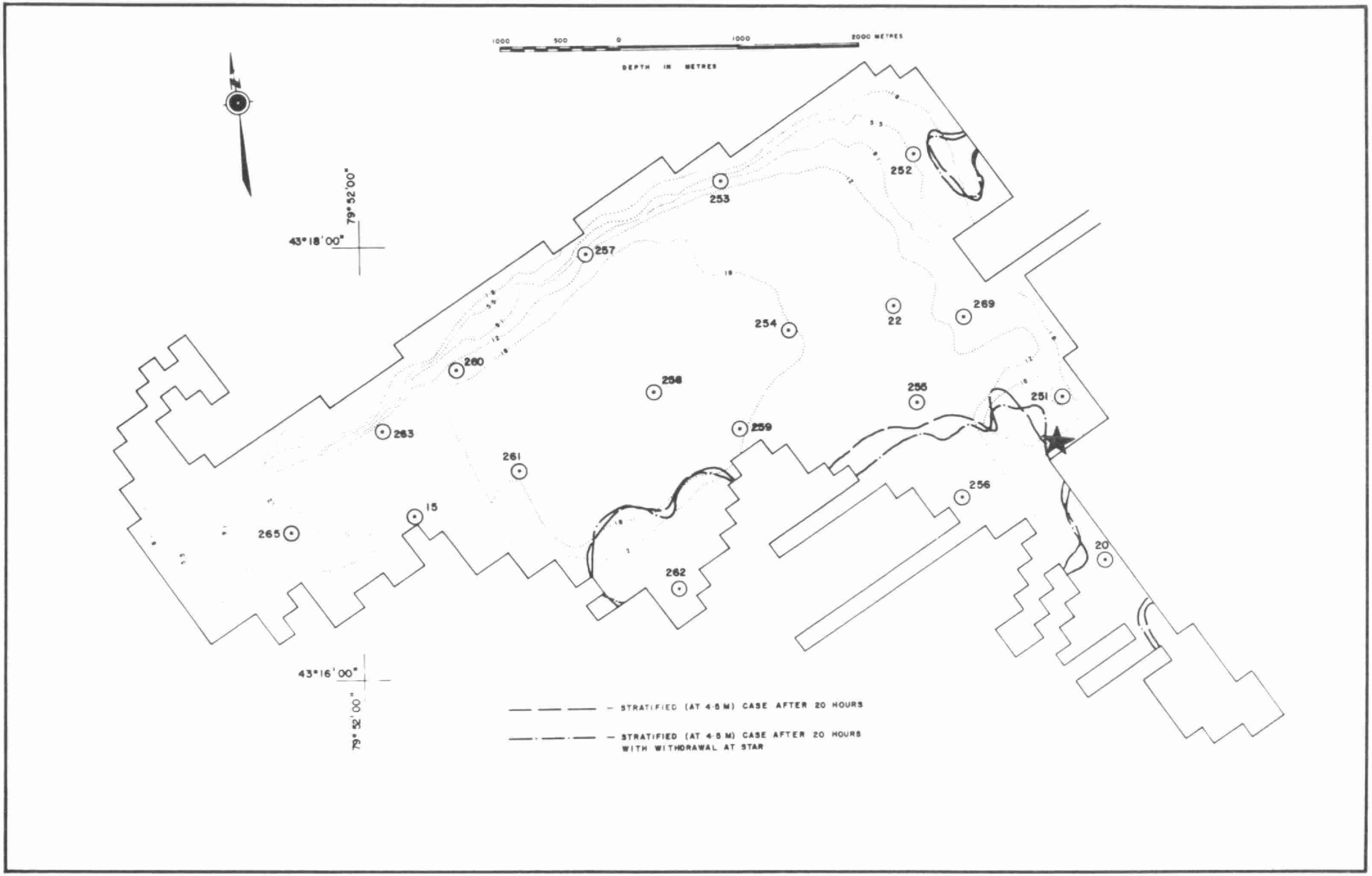


FIGURE 11 : EFFECT OF WITHDRAWAL

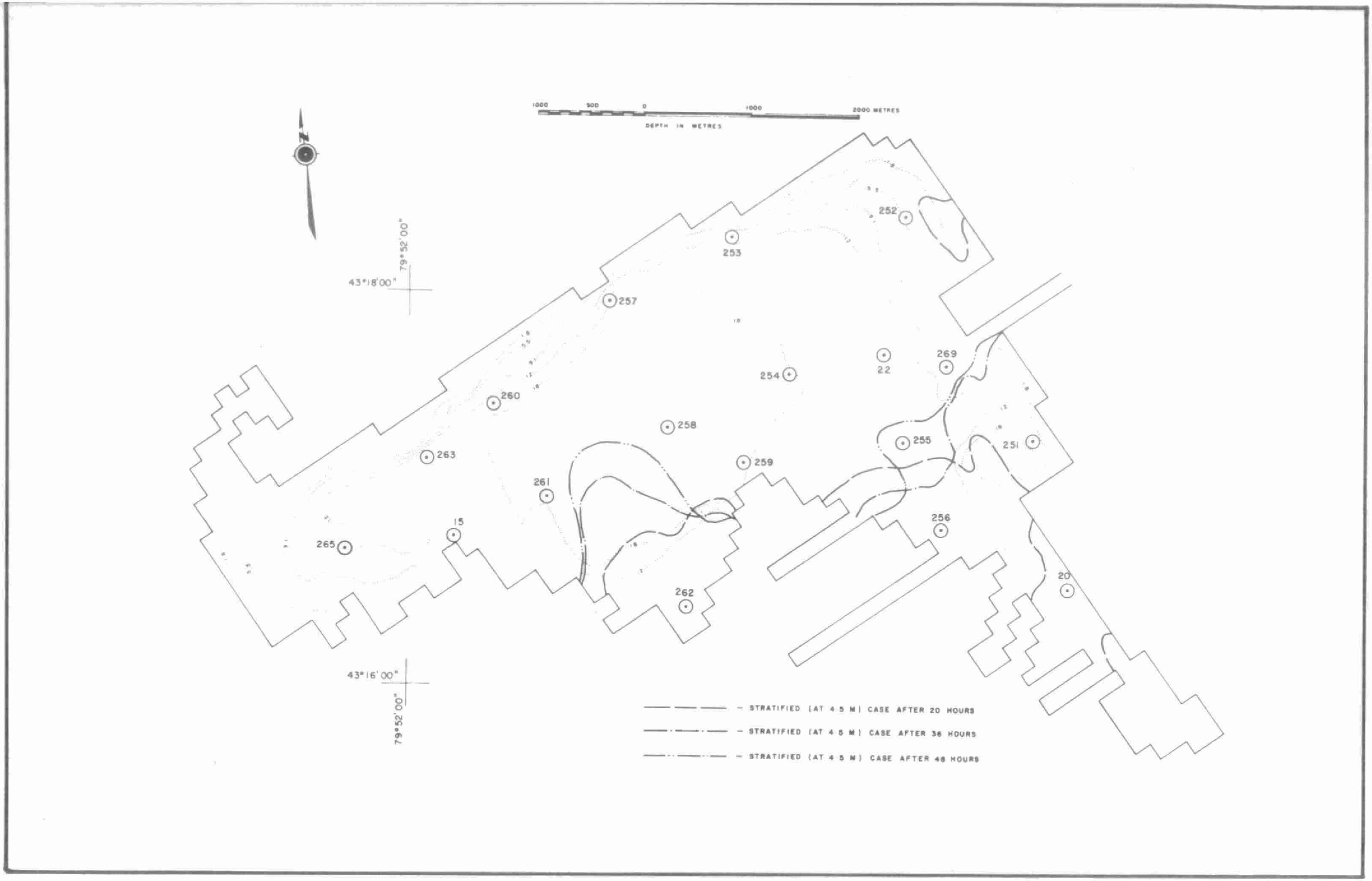


FIGURE 12 : MODEL PREDICTIONS AT DIFFERENT TIMES

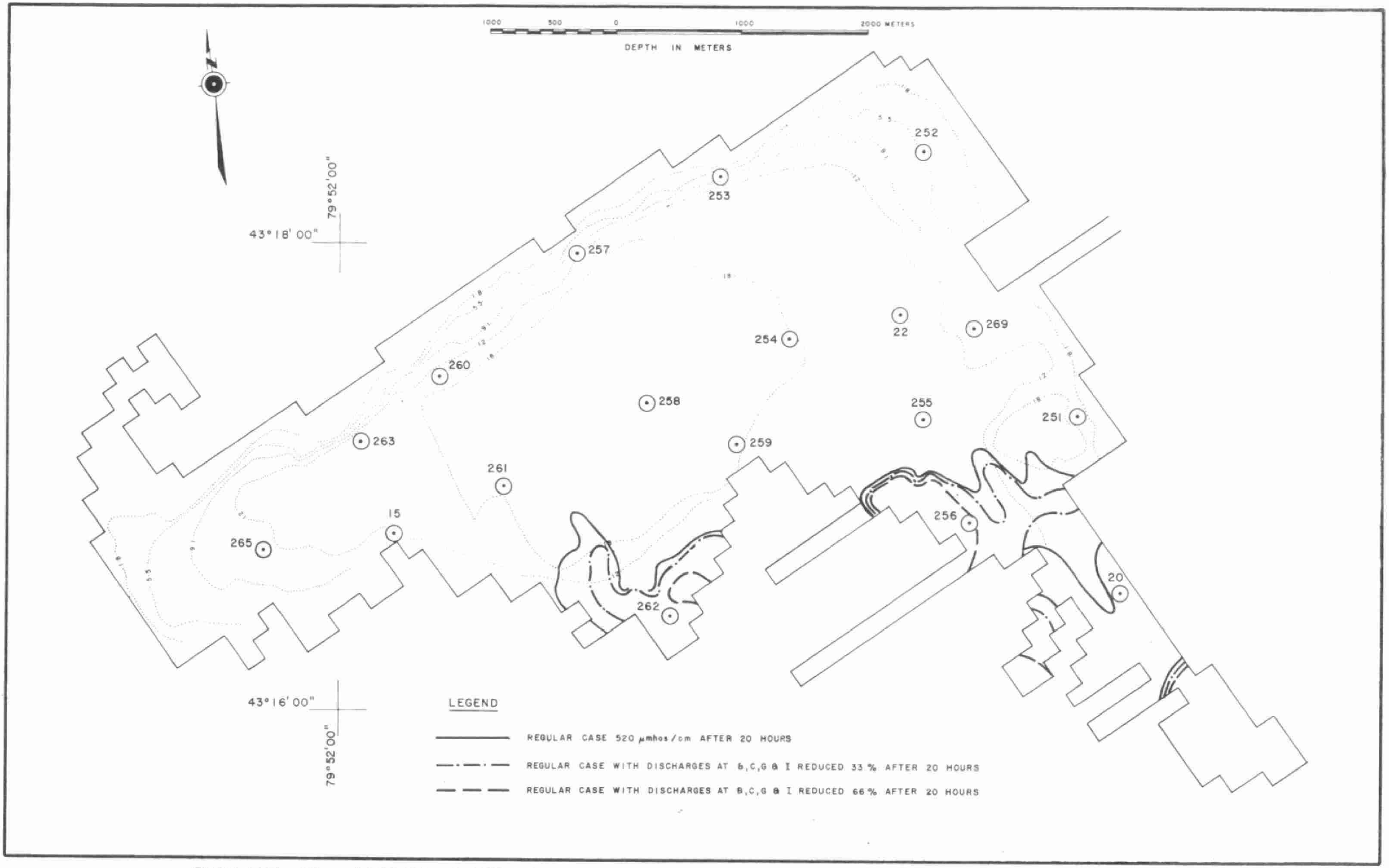


FIGURE 13 : MODEL PREDICTIONS OF SELECTIVE REDUCTIONS OF LOADINGS

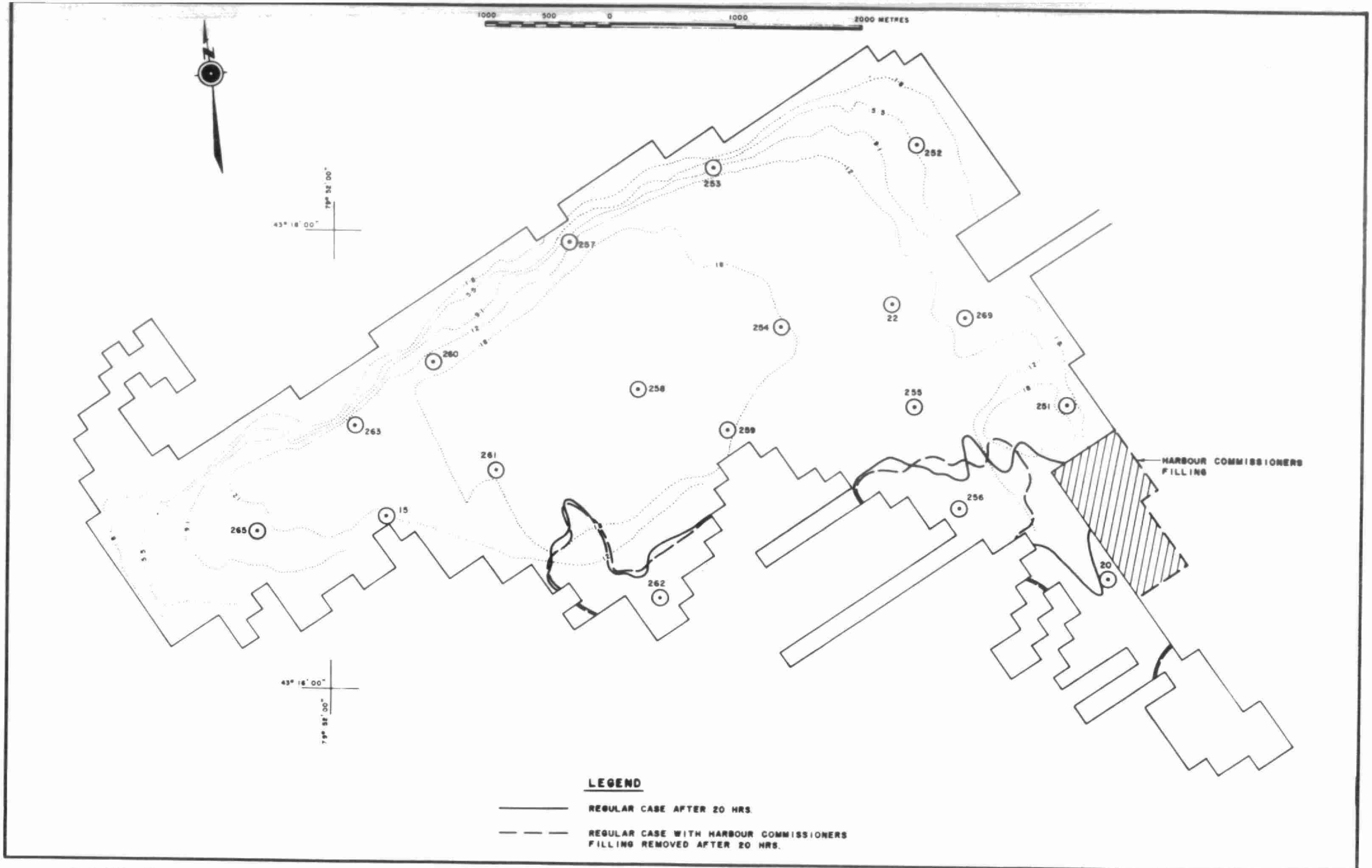


FIGURE 14 : MODEL PREDICTIONS SHOWING THE EFFECT OF HARBOUR COMMISSION FILLING

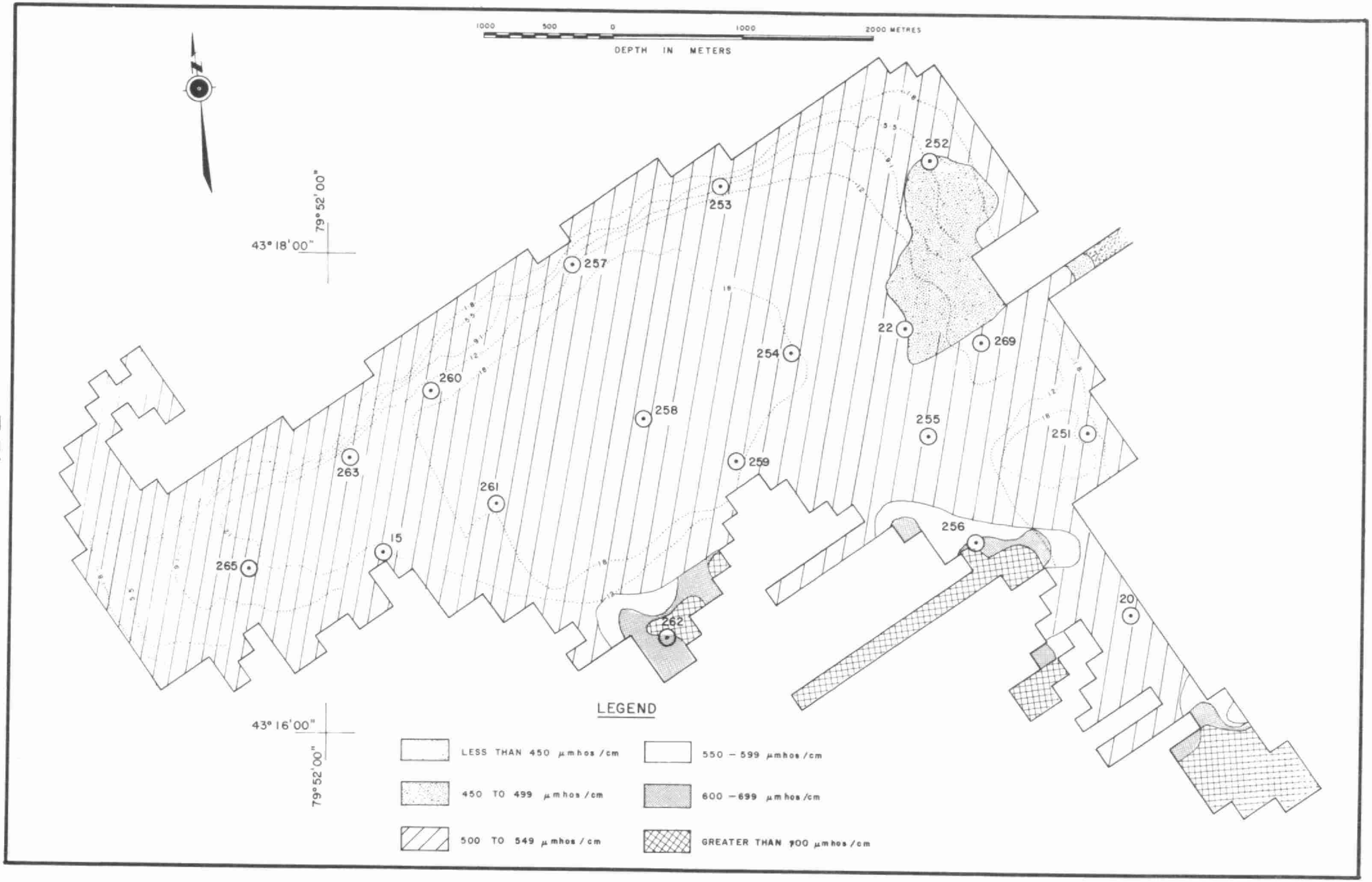


FIGURE 15: MODEL PREDICTIONS REGULAR CASE AFTER 20 HOURS

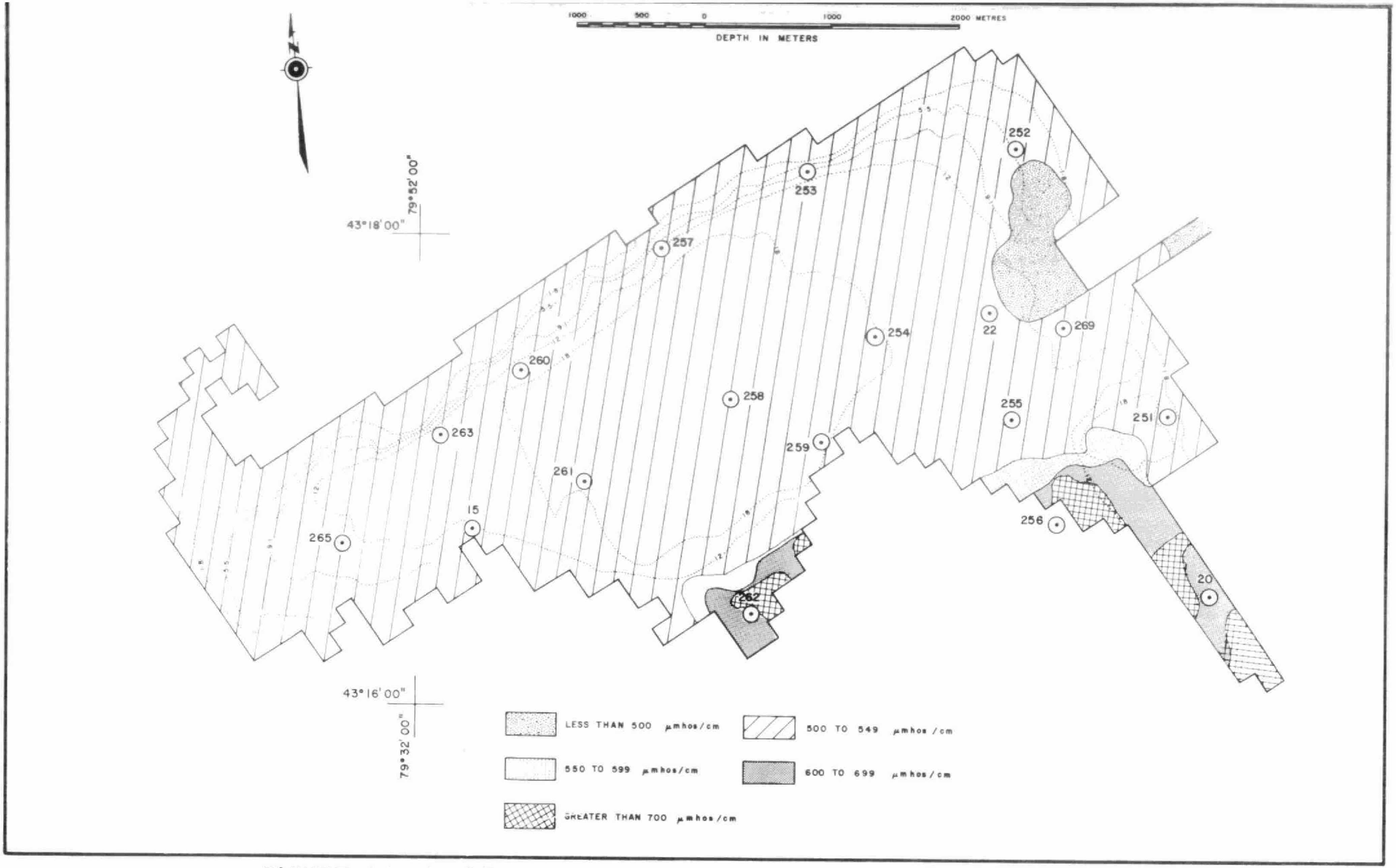


FIGURE 16 : MODEL PREDICTIONS NEW BOUNDARIES AFTER 20 HOURS

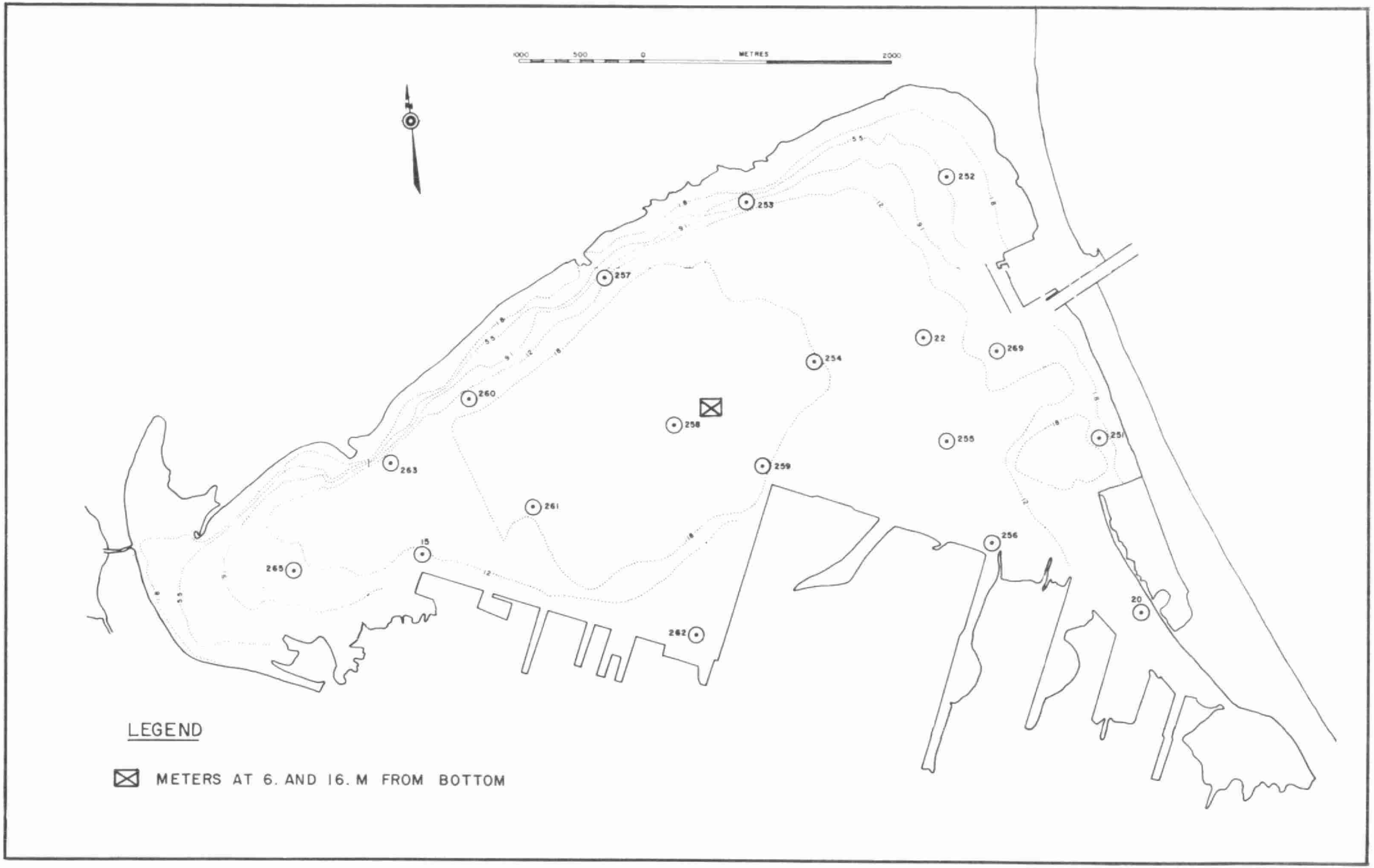


FIGURE 17 : RECORDING CURRENT METERS LOCATION DECEMBER 14 1972 TO FEBRUARY 8 1973

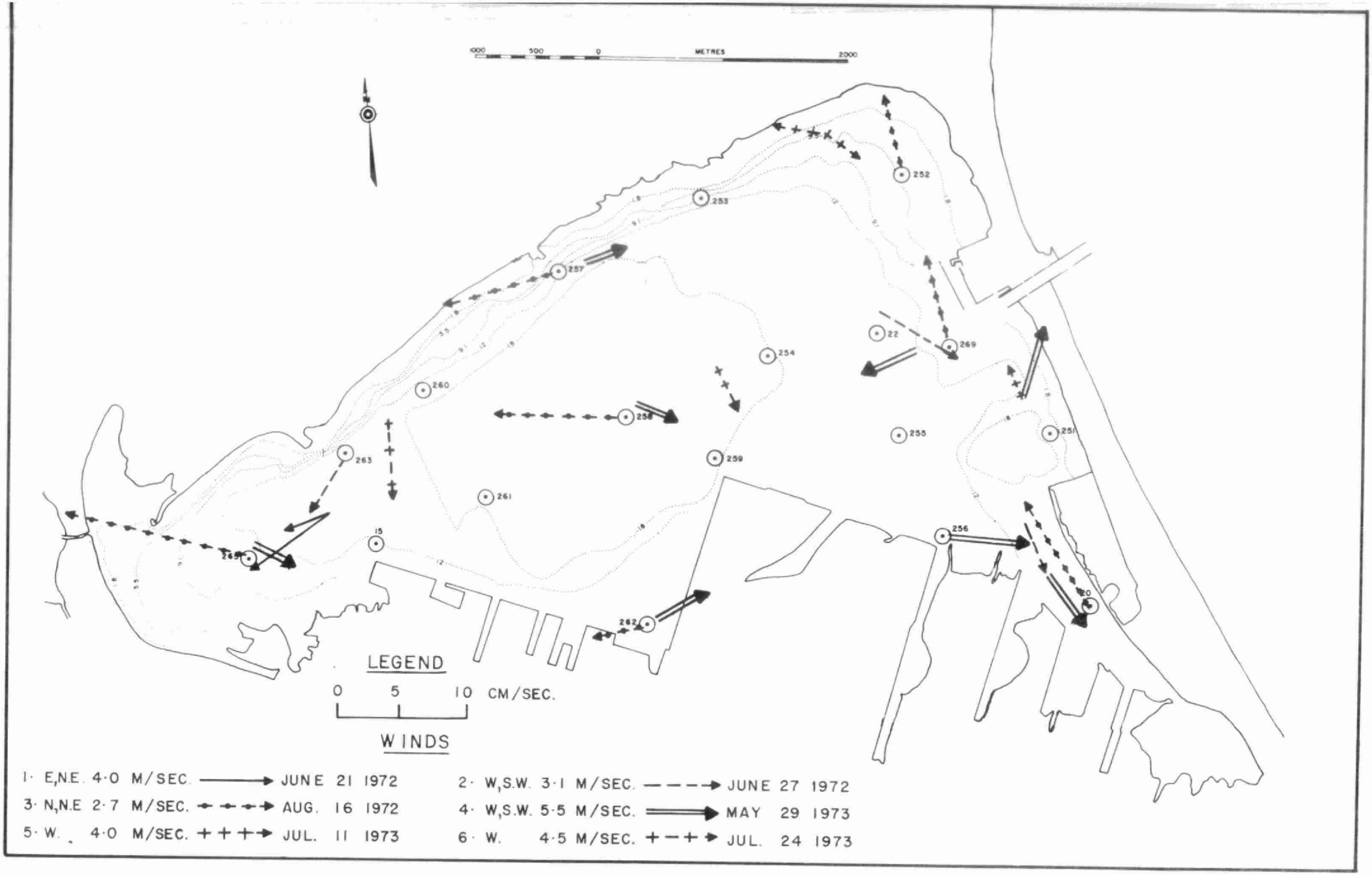


FIGURE 18 : DROGUE MEASUREMENTS

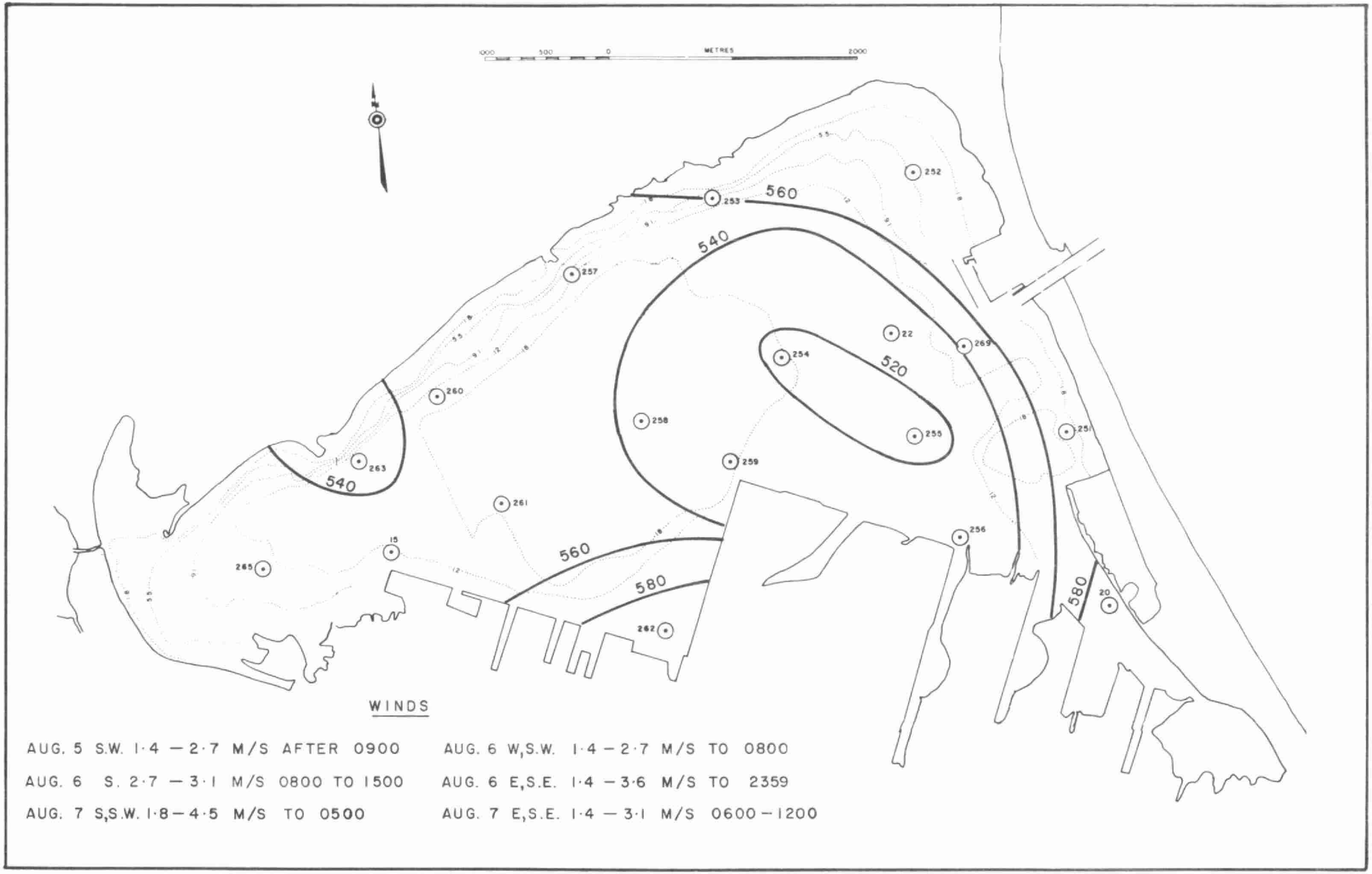


FIGURE 19 : MEAN DEPTH CONDUCTIVITY AUGUST 6 — 7 1972

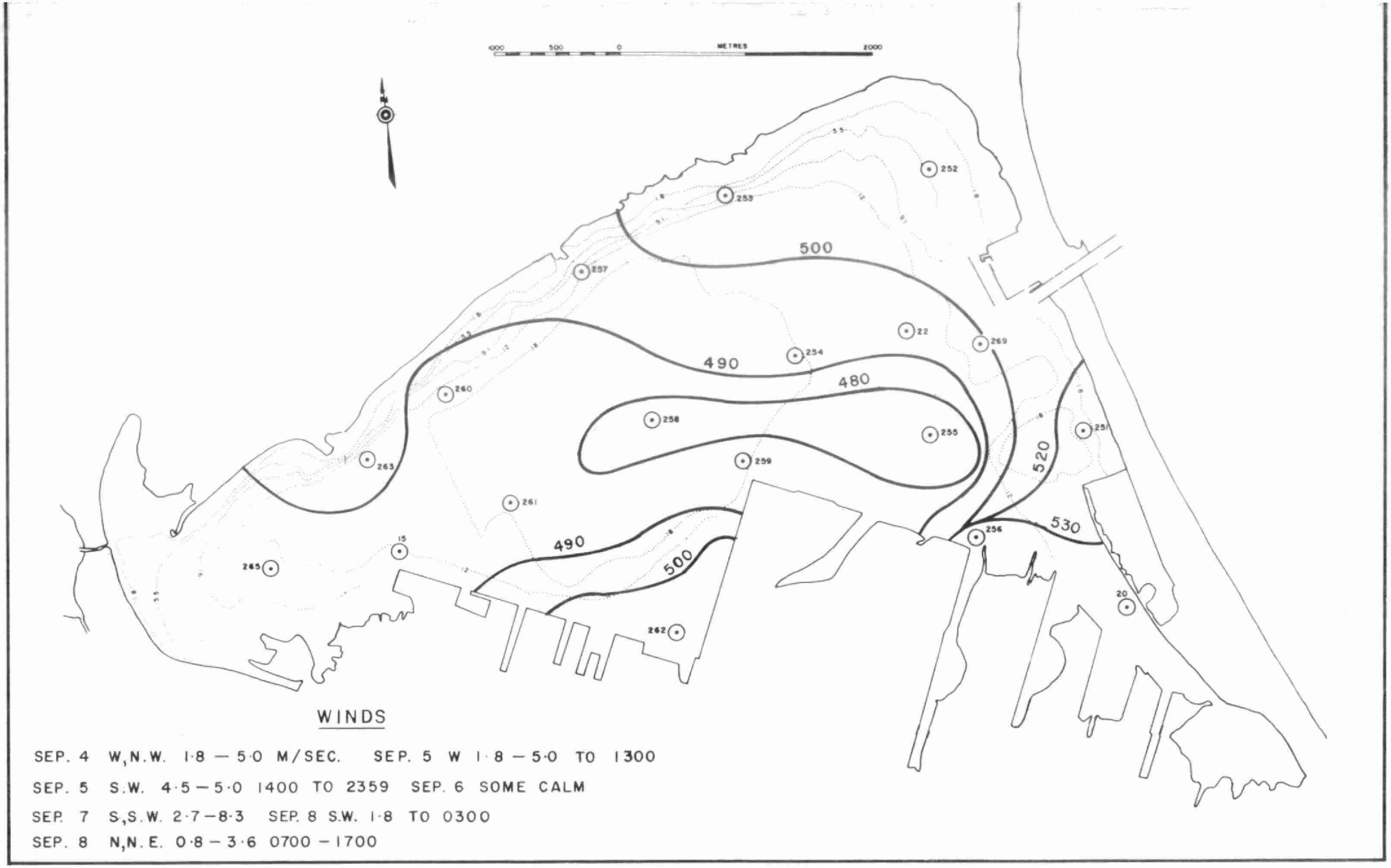


FIGURE 20 : MEAN DEPTH CONDUCTIVITY SEPTEMBER 5 – 8 1972

E 57

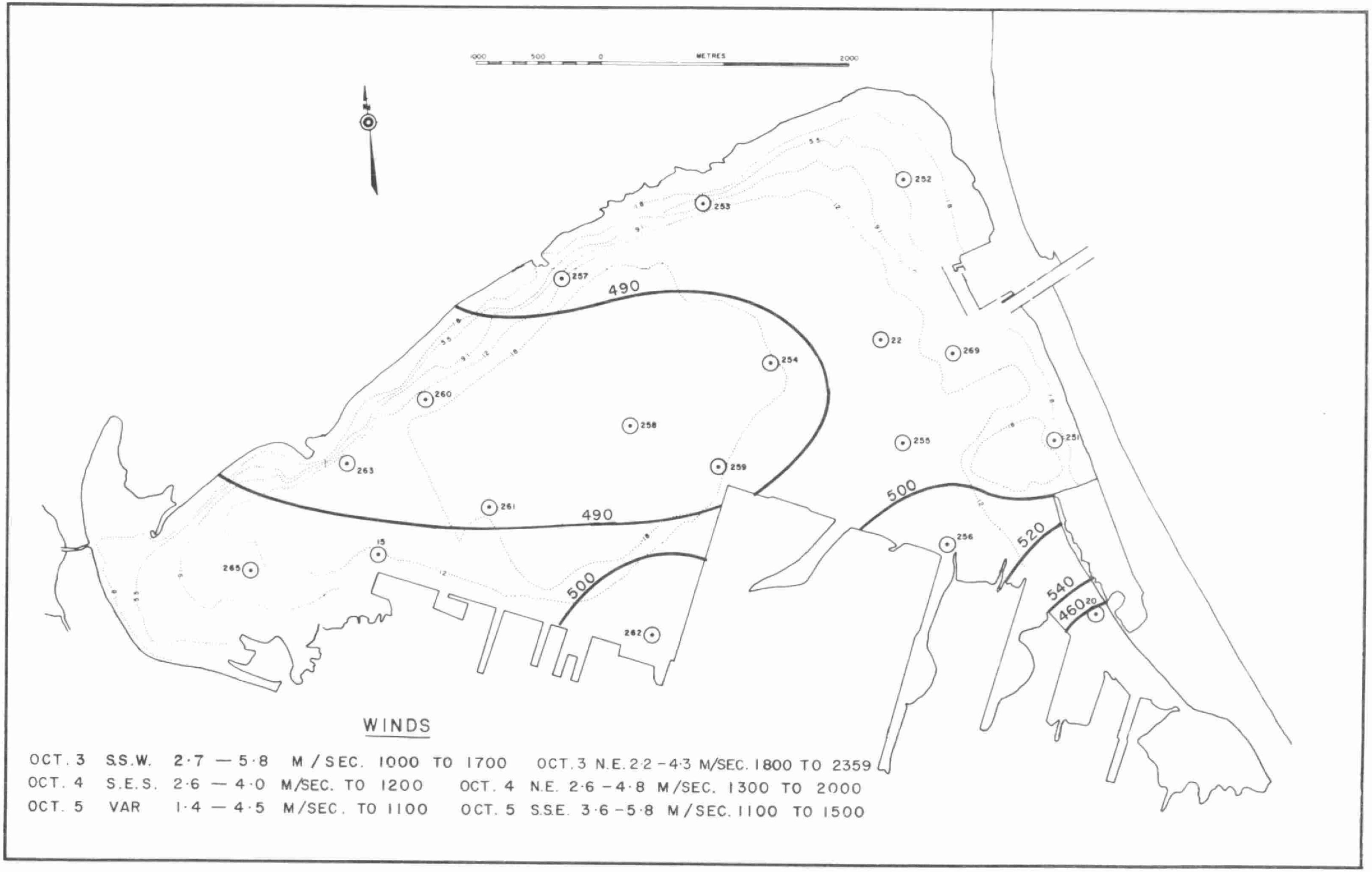


FIGURE 21 : MEAN DEPTH CONDUCTIVITY OCTOBER 4 – 5 1972

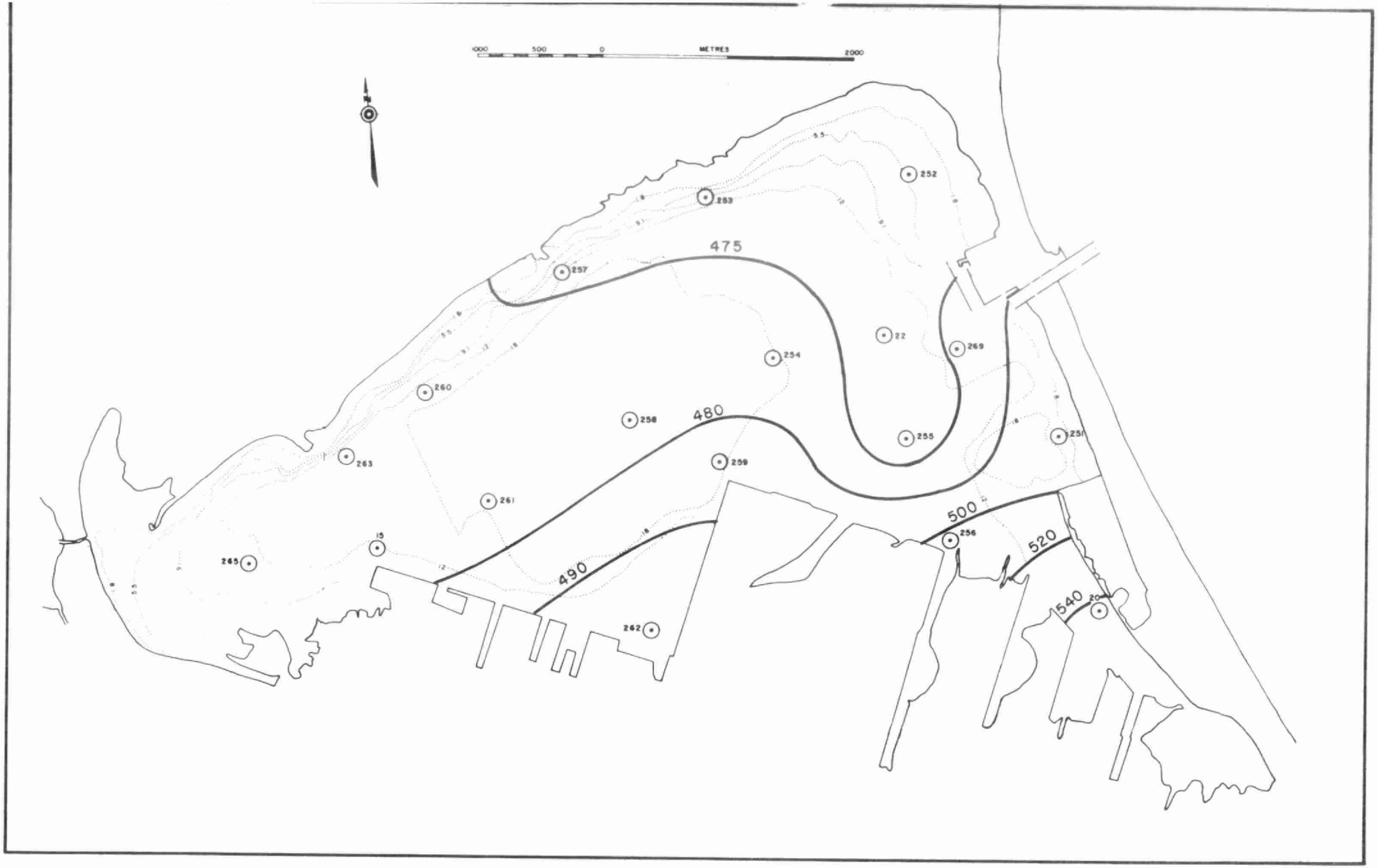


FIGURE 22: MEAN DEPTH CONDUCTIVITY OCTOBER 31 – NOVEMBER 1 1972

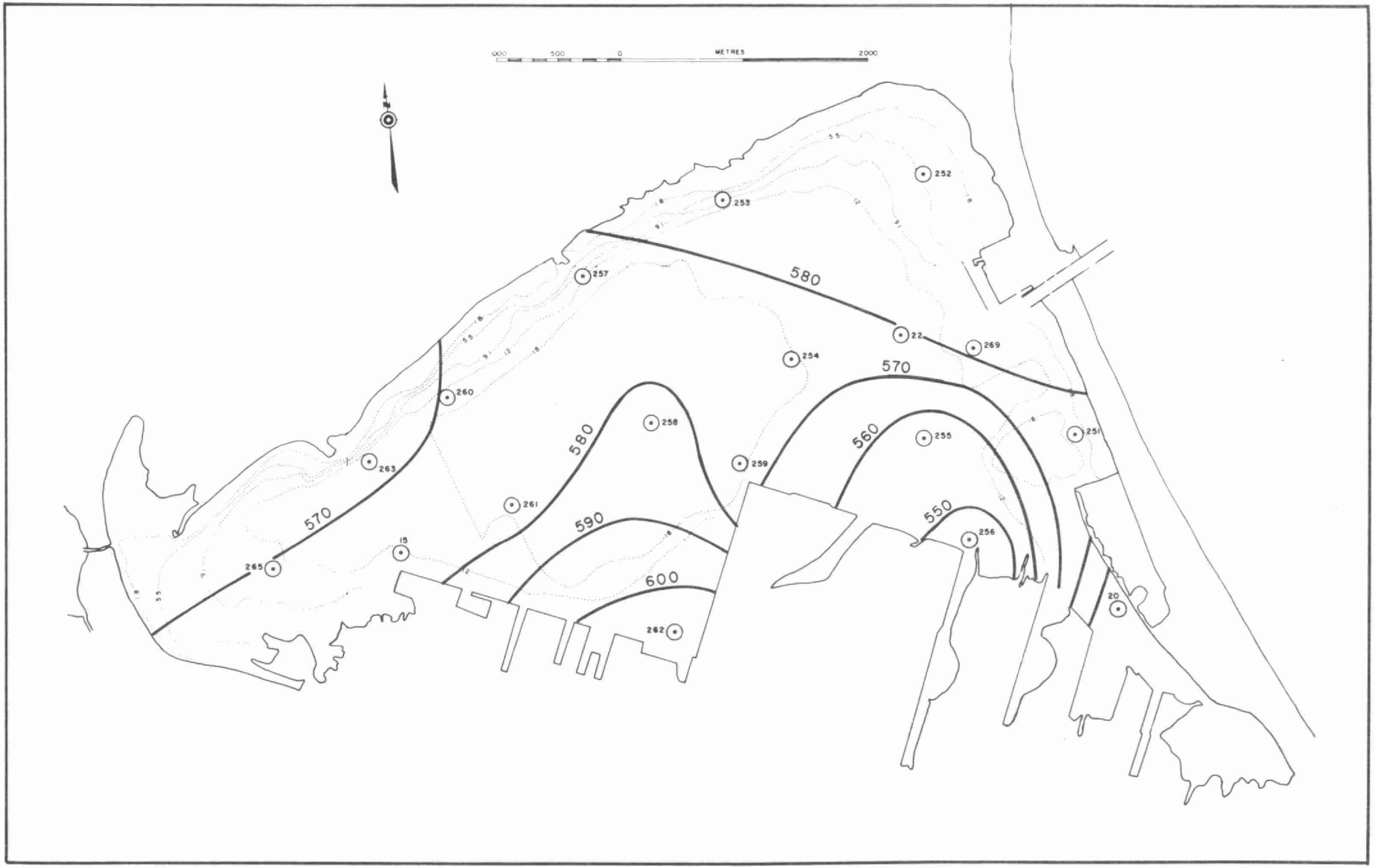


FIGURE 23 : MEAN EPILIMNION CONDUCTIVITY AUGUST 6 – 7 1972

E60

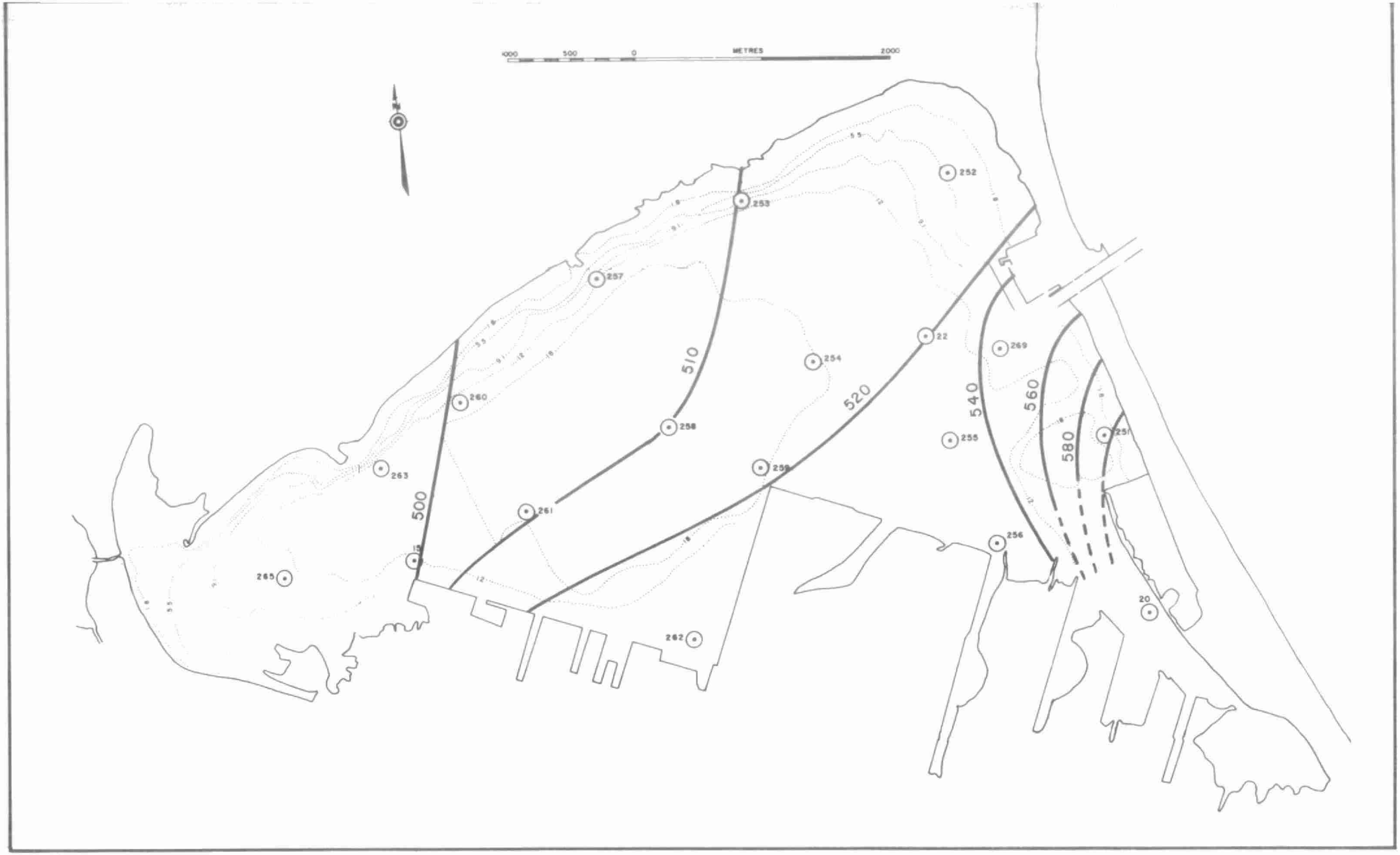


FIGURE 24 : MEAN EPILIMNION CONDUCTIVITY SEPTEMBER 5-8 1972

FIGURE 25 : MEAN EPILIMNION CONDUCTIVITY OCTOBER 4-5 1972

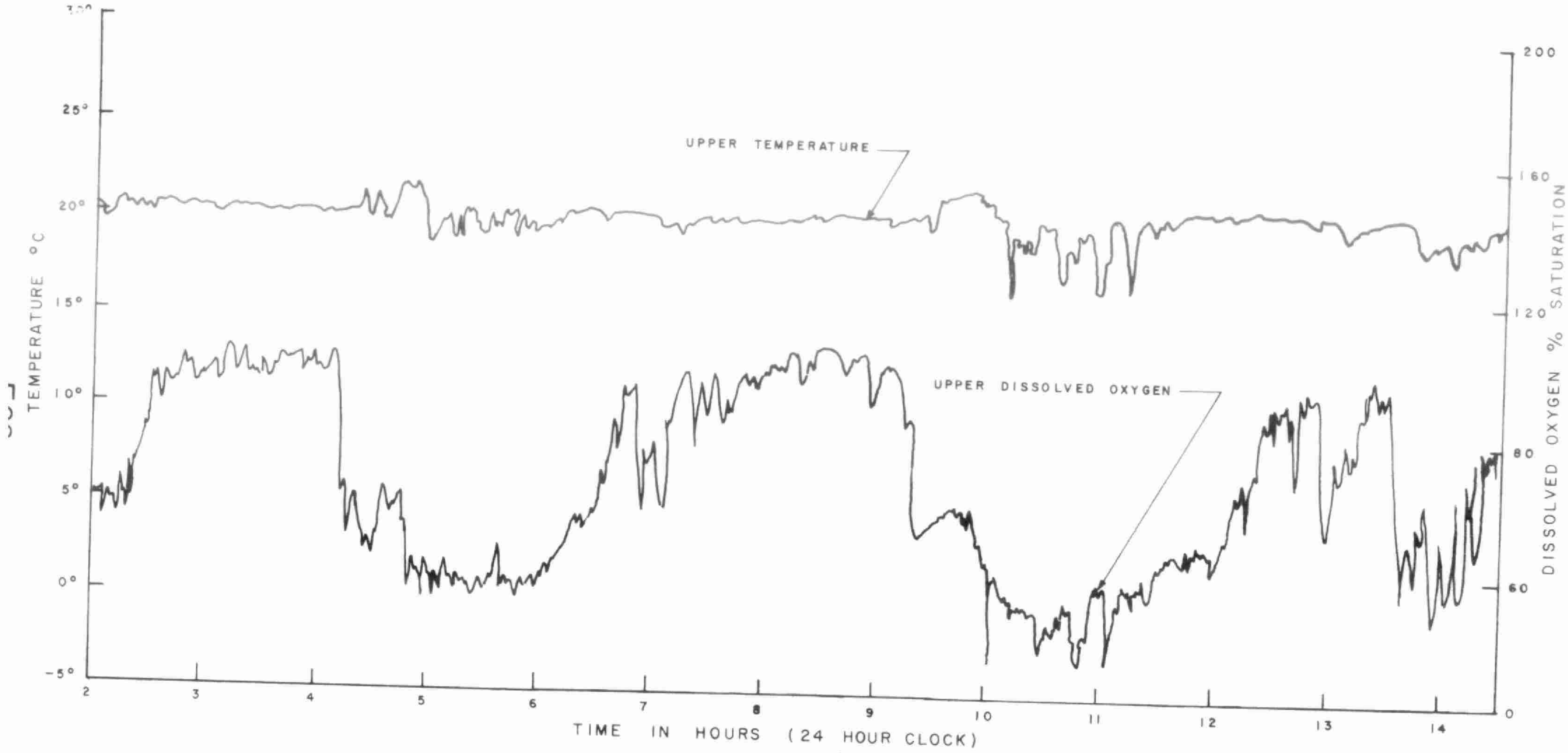


FIGURE 26 : RECORDING CHEMISTRY METER IN SHIP'S CANAL AUGUST 19 1973

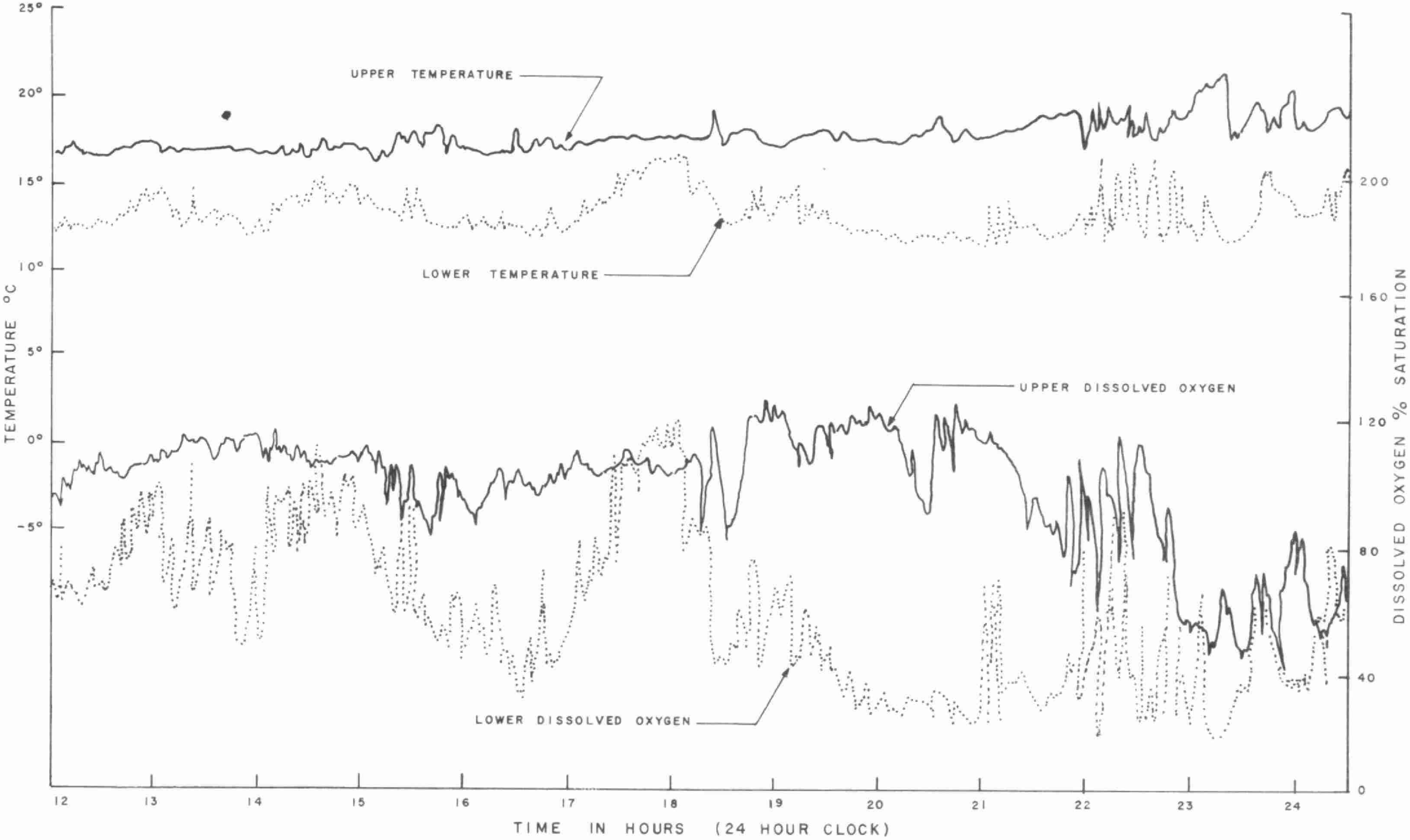


FIGURE 27 : RECORDING CHEMISTRY METER IN SHIP'S CANAL AUGUST 17 1973

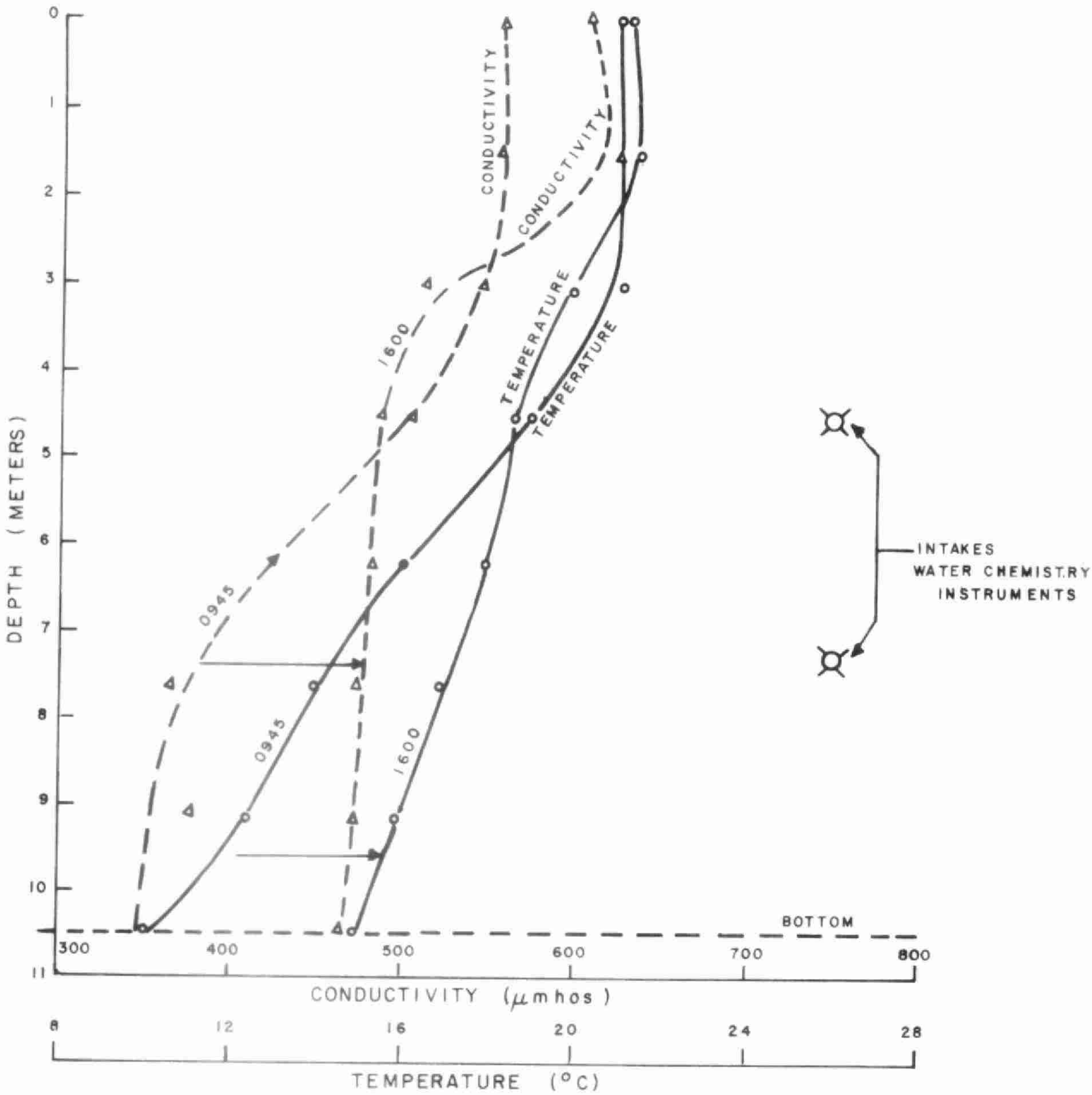


FIGURE 28 : SHIP'S CANAL DEPTH PROFILE
0945 TO 1600 JULY 11 1973

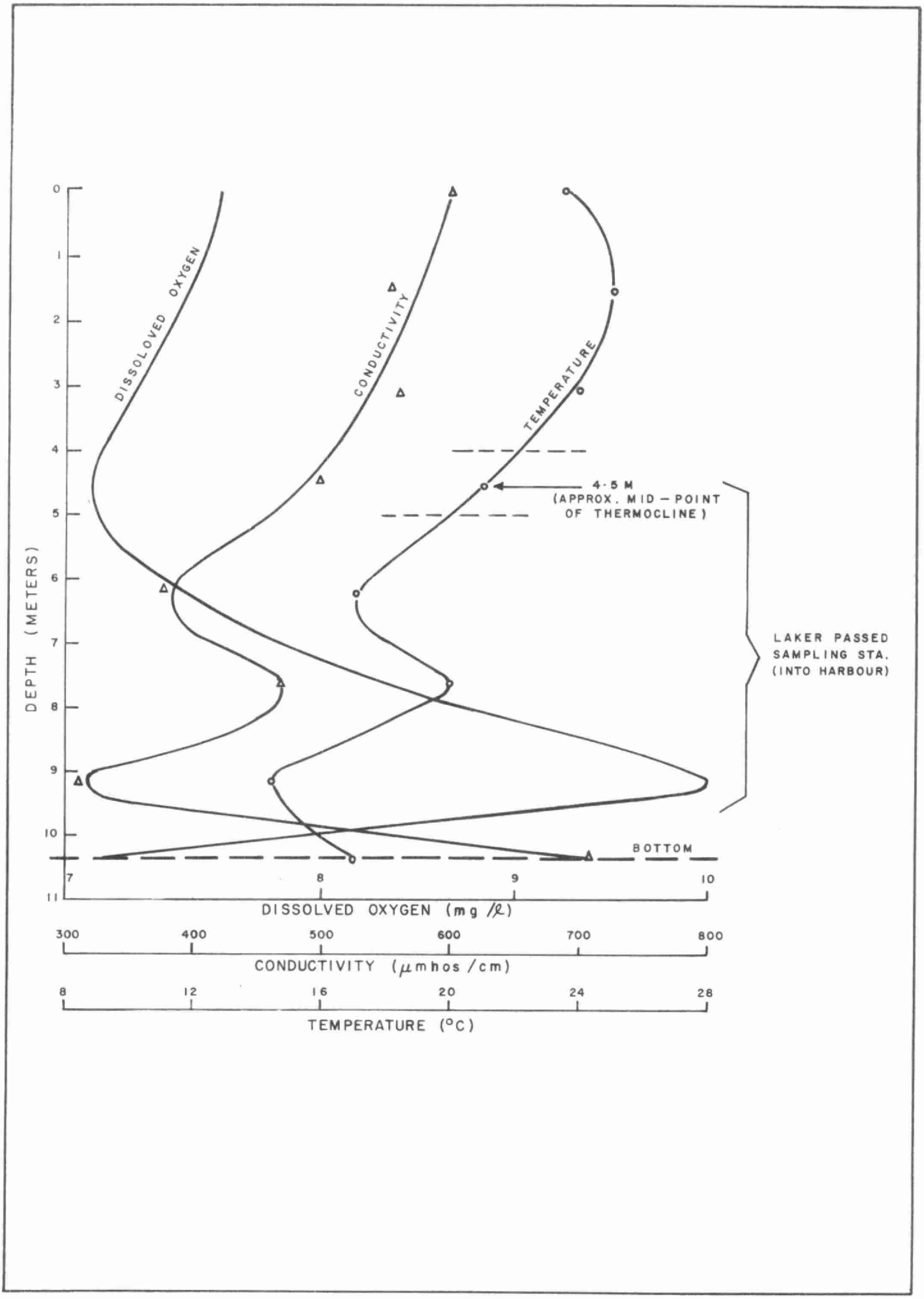


FIGURE 29 : SHIP'S CANAL DEPTH PROFILE
1315 JULY 10 1973

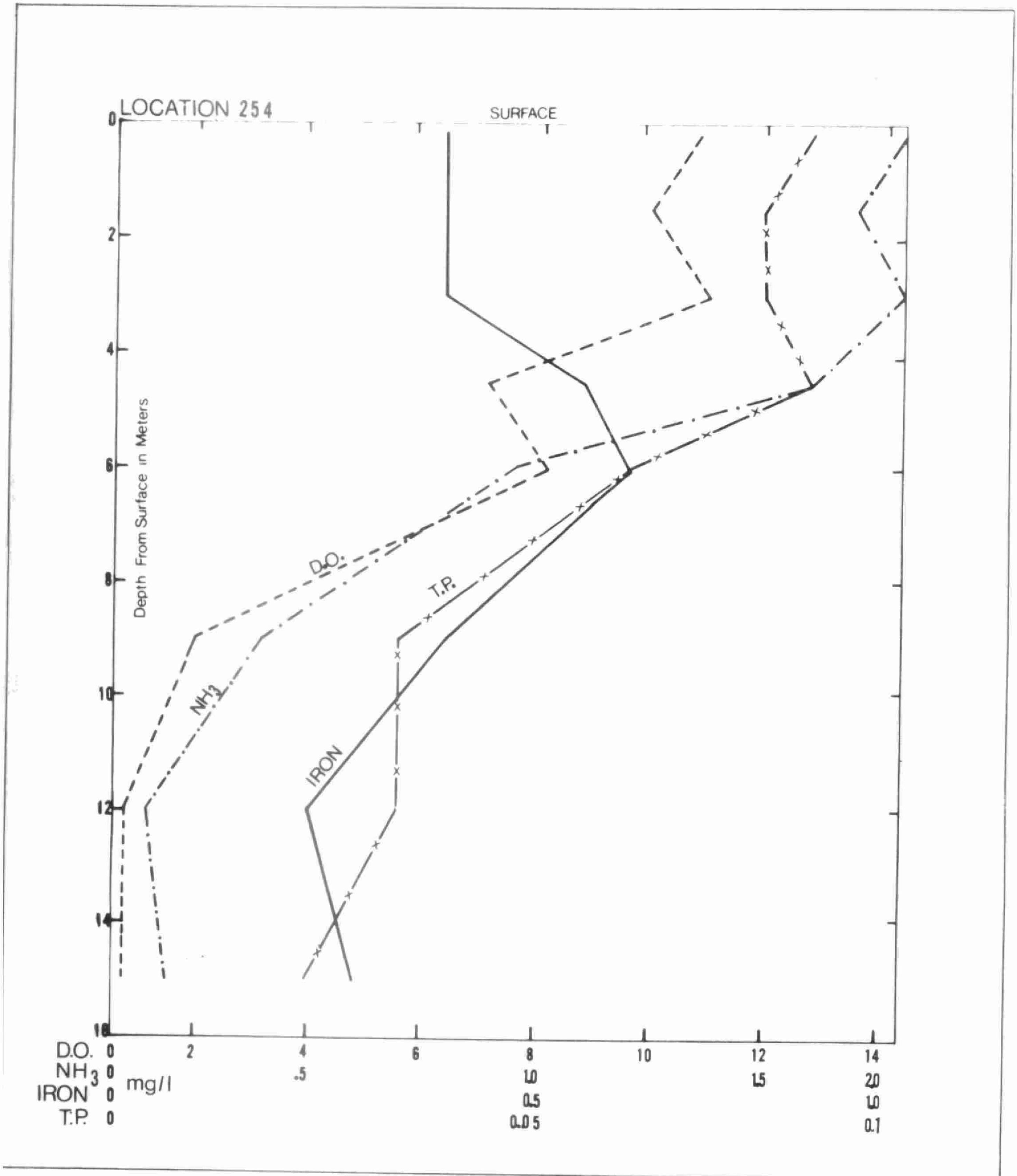


FIGURE 30 DEPTH PROFILES AUGUST 6 1972

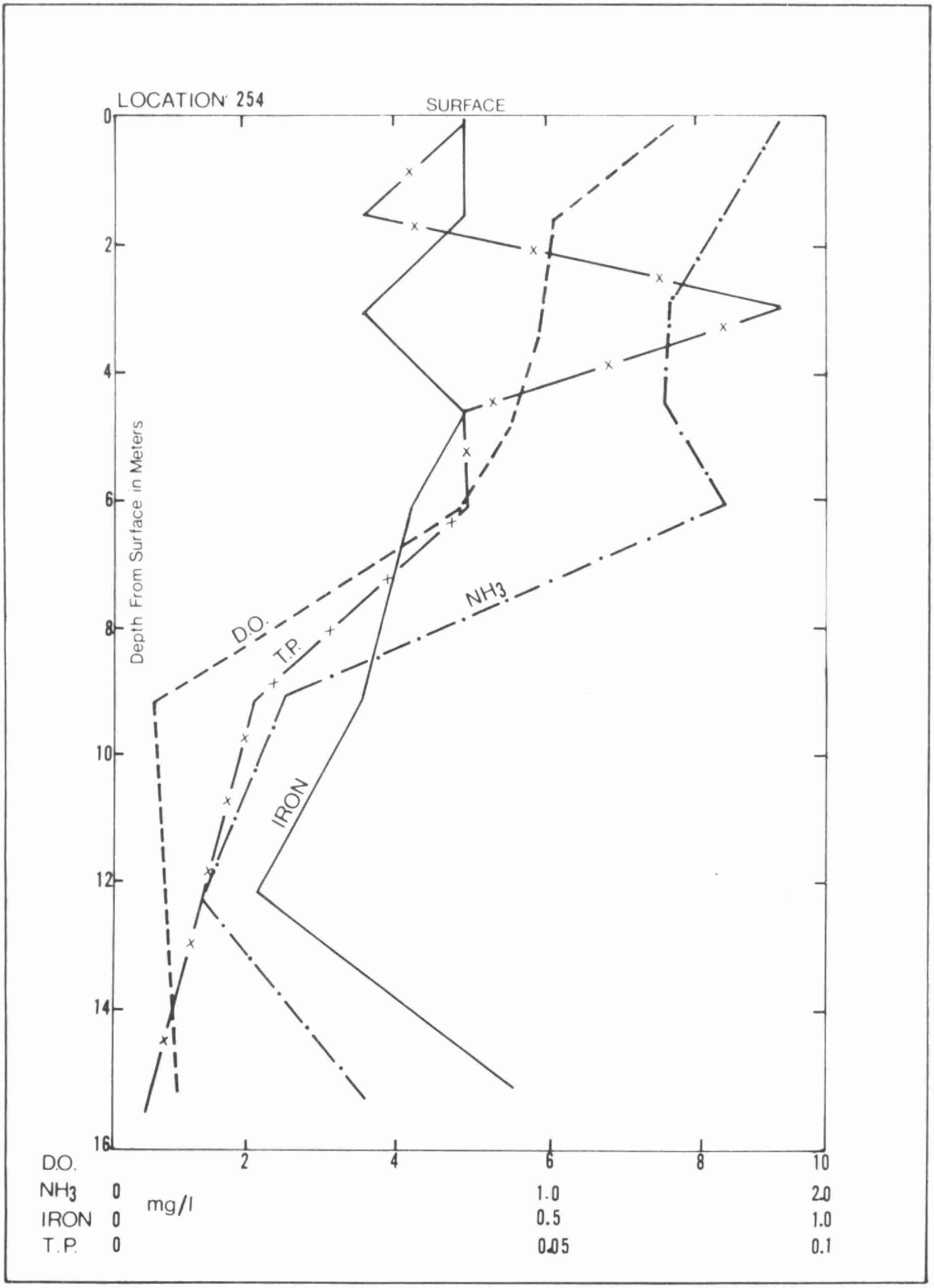
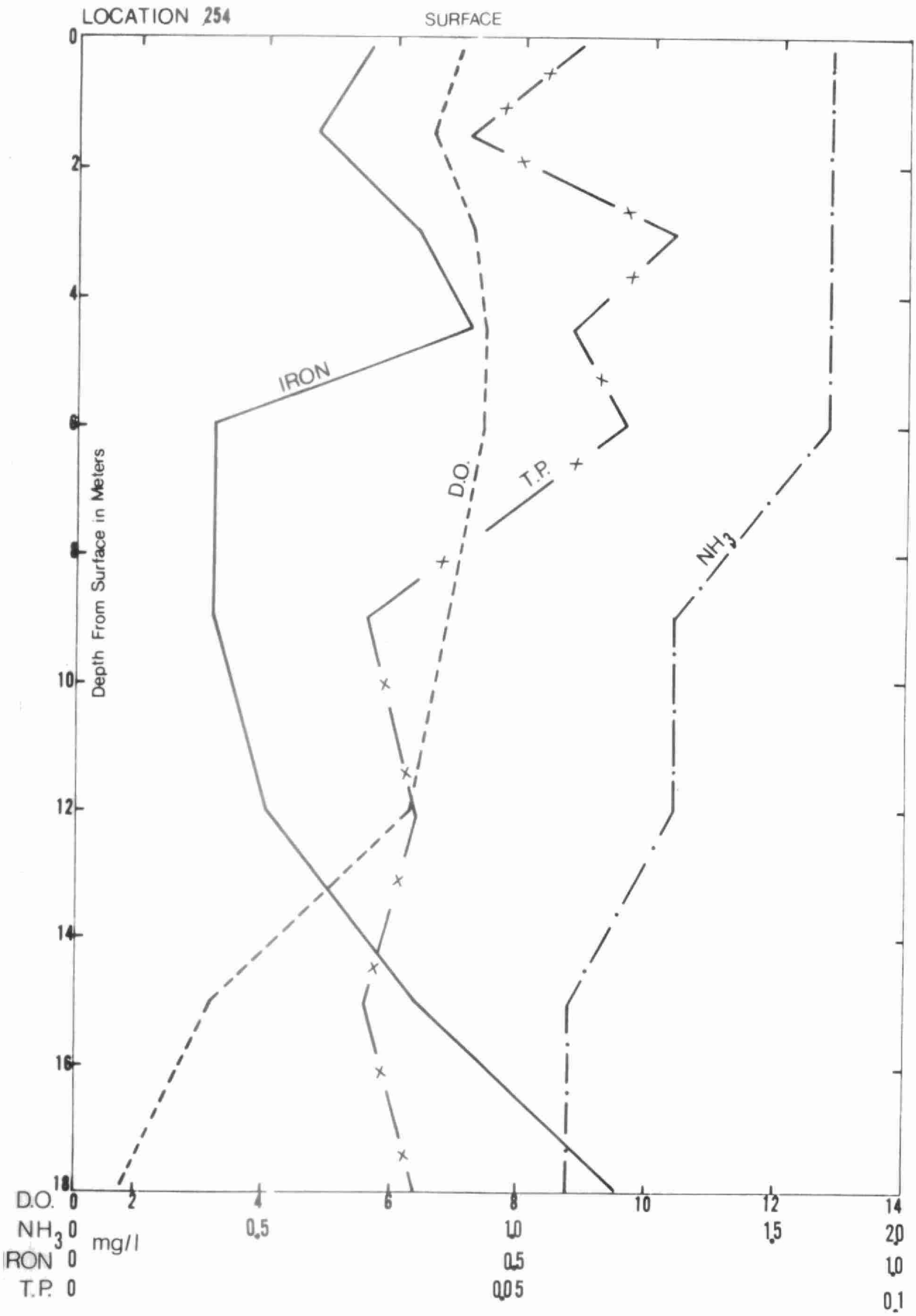


FIGURE 31 DEPTH PROFILES SEPTEMBER 6 1972



IGURE 32 DEPTH PROFILES OCTOBER 5 1972

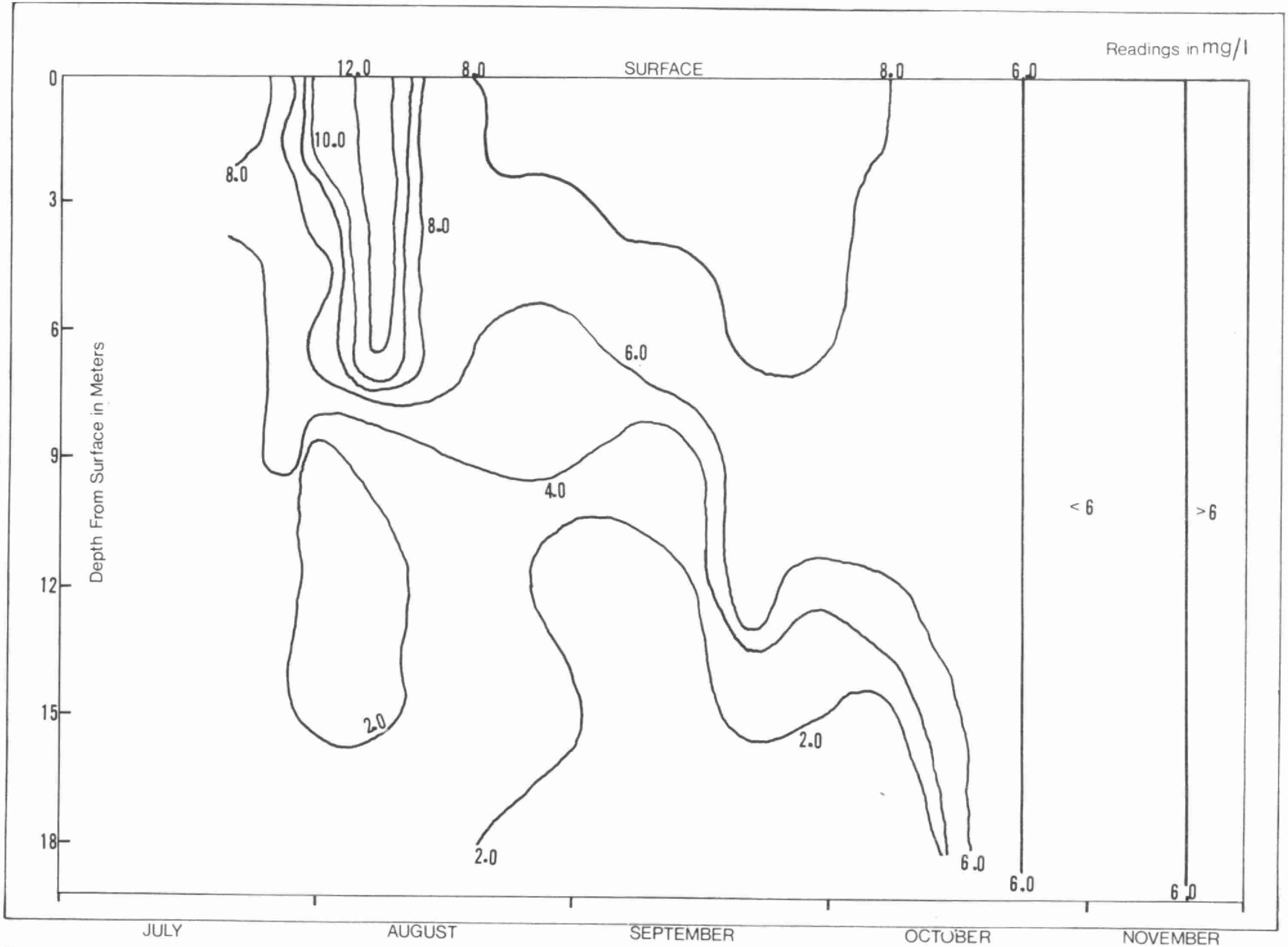


FIGURE 33

DISSOLVED OXYGEN ISOPLETH
STATION 258

APPENDIX

Development of Numerical Model

The movement of the water in Hamilton Harbour as well as the pollutant dispersion is three-dimensional and time variant. The solution of such a situation is mathematically difficult. The two-dimensional solution developed here assumes that the flow field and contaminant fields are homogeneous with depth. Consequently, the general equations of motion and mass transport may be simplified somewhat by integrating with depth to produce the following equations:

MOMENTUM

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV + g\frac{\partial \zeta}{\partial x} + g\frac{U(U^2 + V^2)^{\frac{1}{2}}}{C^2 H} - \frac{1}{\rho H}\tau_x^s + \frac{US}{H} = 0$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU + g\frac{\partial \zeta}{\partial y} + g\frac{V(U^2 + V^2)^{\frac{1}{2}}}{C^2 H} - \frac{1}{\rho H}\tau_y^s + \frac{VS}{H} = 0$$

CONTINUITY

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (HU)}{\partial x} + \frac{\partial (HV)}{\partial y} = S$$

where

f = Corriolis parameter

g = acceleration of gravity

C = Chezy coefficient

τ_x^s = component of the wind stress in the x direction

τ_y^s = component of the wind stress in the y direction

ρ = water density

S = external sources & sinks for water

MASS TRANSPORT

$$\frac{\partial (H\bar{P})}{\partial t} + \frac{\partial (HU\bar{P})}{\partial x} + \frac{\partial (HV\bar{P})}{\partial y} - \frac{\partial \left[HD_x \frac{\partial \bar{P}}{\partial x}\right]}{\partial x} - \frac{\partial \left[HD_y \frac{\partial \bar{P}}{\partial y}\right]}{\partial y} + [K]H\bar{P} + H\bar{S} = 0$$

where: S - water level elevation relative to reference plane

h - depth from reference plane to bottom

H - h + ζ

$\bar{S}_A$ - source function vector

$\bar{P}$ - mass concentration vector

[K] - reaction matrix

D - diffusion coefficient

The solution of these equations has been undertaken using a numerical scheme proposed by J.J. Leendertse of the Rand Corporation. The discreet values of the variable are described on a space-staggered grid outlined below.

```
        + - + - +  k+1

        l o l o l

        + - + - +  k

   Y    l o l o l

        + - + - +  k-1

        j-1 j   j+1

                  X
```

where: + = water level ζ and pollutant concentration P

o = depth

\- = U velocity

l = V velocity

This scheme allows for spatial averaging of some of the terms in the numerical approximation which enhances the numerical stability of the system. The solution of the equations is also staggered in time with two time levels for each time step for the same reasons as indicated above.

The following notation (for the general function F) is used in developing the finite difference equations:

$$F = F(j\Delta k,\ k\Delta y,\ h\Delta t)$$

where the coordinate (x,y,t) is represented approximately on the finite grid by:

$$(j\Delta x,\ k\Delta y,\ n\ t) \quad \text{with} \quad j,k,n = 0,\ \pm 1/2,\ \pm 1,\ \pm 3/2,\ \text{etc.}$$

The following averages and differentials are used in the representation and for brevity are shown only for 'x' although they apply also to 'y' and 't'.

$$\overline{F}^{x} = \tfrac{1}{2}\{F[(j + \tfrac{1}{2})\Delta x,\ k\Delta y,\ n\Delta t] + F[(j - \tfrac{1}{2})\Delta x,\ k\Delta y,\ n\Delta t]\}$$

$$\delta_x F = \frac{1}{\Delta x}\{F[(j + \tfrac{1}{2})\Delta x,\ k\Delta y,\ n\Delta t] - F[(j - \tfrac{1}{2})\Delta x,\ k\Delta y,\ n\Delta t]\}$$

$$\begin{aligned}\overline{F} = \tfrac{1}{4}\{&F[(j + \tfrac{1}{2})\Delta x,\ (k + \tfrac{1}{2})\Delta y,\ n\Delta t] + F[(j + \tfrac{1}{2})\Delta x,\ (k - \tfrac{1}{2})\Delta y,\ n\Delta t] \\ &+ F[(j - \tfrac{1}{2})\Delta x,\ (k + \tfrac{1}{2})\Delta y,\ n\Delta t] + F[(j - \tfrac{1}{2})\Delta x,\ (k - \tfrac{1}{2})\Delta y,\ n\Delta t]\}\end{aligned}$$

The following special notation is used specifically for 't' to indicate shifted time levels.

$$\delta_{+\frac{1}{2}t} F = \frac{2}{\Delta t}\{F[j\Delta x,\ k\Delta y,\ (n + \tfrac{1}{2})\Delta t] - F(j\Delta x,\ k\Delta y,\ n\Delta t)\}$$

$$F_{+} = F[j\Delta x,\ k\Delta y,\ (n + \tfrac{1}{2})\Delta t]$$

$$F_{-} = F[j\Delta x,\ k\Delta y,\ (n - \tfrac{1}{2})\Delta t]$$

$$\overline{F}^{t/2} = \tfrac{1}{2}\{F[j\Delta x,\ k\Delta y,\ (n + \tfrac{1}{2})\Delta t] + F[j\Delta x,\ k\Delta y,\ n\Delta t]\}$$

The set of finite difference equations used to approximate the momentum and mass balance equations are as follows:

<u>Momentum Equations</u>

1/ (at point $j+\frac{1}{2},k,n$)

$$\delta_t u - f\overline{\overline{v}} + u_{+}\overline{\delta_x u_{-}}^{x} + \overline{\overline{v}}\overline{\delta_y u_{-}}^{y} + g\overline{\delta_x \zeta}^{t}$$

$$+ g\,\frac{\overline{u}^{t}[(u_{-})^2 + (\overline{\overline{v}})^2]^{\frac{1}{2}}}{(\overline{h}^{y} + \overline{\zeta}^{x})(\overline{C}^{x})^2} - \frac{1}{\rho(\overline{h}^{y} + \overline{\zeta}^{x})}\,\tau_x^{s} + \frac{\overline{u}^{t}S}{(\overline{h}^{y} + \overline{\zeta}^{x})} = 0$$

2/ (at point $j,k+\frac{1}{2},n+\frac{1}{2}$)

$$\delta_t v + f\bar{\bar{u}} + \overline{\bar{u}\delta_x v_-}^x + v_+\overline{\delta_y v_-}^y + g\overline{\delta_y \zeta}^t$$

$$+ g\frac{\bar{v}^t[(\bar{\bar{u}})^2 + (v_-)^2]^{\frac{1}{2}}}{(\bar{h}^x + \bar{\zeta}^y)(\bar{C}^y)^2} - \frac{1}{\rho(\bar{h}^x + \bar{\zeta}^y)}\tau_y^s + \frac{\bar{v}^t S}{(\bar{h}^y + \bar{\zeta}^x)} = 0$$

Continuity Equations

1/ (at point j,k,n)

$$\delta_{+\frac{1}{2}t}\zeta + \delta_x[\bar{h}^y + \bar{\zeta}^x)u_+] + \delta_y[(\bar{h}^x + \bar{\zeta}^y)v\ ] = S$$

2/ (at point $j,k,n+\frac{1}{2}$)

$$\delta_{+\frac{1}{2}t}\zeta + \delta_x[(\bar{h}^y + \bar{\zeta}^x)u] + \delta_y[(\bar{h}^x + \bar{\zeta}^y)v_+] = S$$

Mass Balance Equations (for constitutent i)

$$\delta_{+\frac{1}{2}t}[P_i(\bar{\bar{h}} + \zeta)] + \delta_x[(\bar{h}^y + \bar{\zeta}^x)u_+\bar{P}^x_{i_+}] + \delta_y[(\bar{h}^x + \bar{\zeta}^y)v\bar{P}^y_i]$$

$$- \delta_x[(\bar{h}^y + \bar{\zeta}^x_+)D_{x_+}\delta_x P_{i_+}] - \delta_y[(\bar{h}^x + \bar{\zeta}^y)D_y\delta_y P_i]$$

$$+ \sum_{\ell=1}^{i-1}(\bar{\bar{h}} + \zeta_+)K_{i\ell}P_{\ell_+}\alpha_i + \overline{(\bar{\bar{h}} + \zeta)K_{ii}P_i}^{t/2} + \sum_{\ell=i+1}^{\ell_{max}}(\bar{\bar{h}} + \zeta)K_{i\ell}P_\ell\beta_i$$

$$+ (\bar{\bar{h}} + \zeta)S_i = 0$$

where

$$\alpha_i = \begin{cases} 0 & i = 1 \\ 1 & 1 < i \le \ell_{max} \end{cases}$$

$$\beta_i = \begin{cases} 0 & i = \ell_{max} \\ 1 & 1 \le i < \ell_{max} \end{cases}$$

ℓ_{max} = maximum number of constituents

2/ (at point $j,k,n+\frac{1}{2}$)

$$\delta_{+\frac{1}{2}t}[P_i(\bar{\bar{h}} + \zeta)] + \delta_x[(\bar{h}^y + \bar{\zeta}^x)u\bar{P}^x_i] + \delta_y[(\bar{h}^x + \bar{\zeta}^y)v_+\bar{P}^y_{i_+}]$$

$$-\delta_x[(\bar{h}^y + \bar{\zeta}^x)D_x\delta_x P_i] - \delta_y[(\bar{h}^x + \bar{\zeta}^y_+)D_{y_+}\delta_y P_{i_+}]$$

$$+ \sum_{\ell=1}^{i-1} (\bar{\bar{h}} + \zeta)K_{i\ell}P_\ell\alpha_i + \overline{(\bar{\bar{h}} + \zeta)K_{ii}P_i}^{t/2}$$

$$+ \sum_{\ell=i+1}^{\ell_{max}} (\bar{\bar{h}} + \zeta_+)K_{i\ell}P_{\ell_+}\beta_i$$

The equations 1 shown for each type above are solved in the order given to find U, ζ, and P at the time level n+½. The equations 2 shown above are then solved to calculate V, ζ, and P at time level n+1. For the purpose of expanding these equations to show the solution technique only the set of equations marked 1 above will be used. The other set may be solved in an analogous manner.

Expanding the continuity equation in terms of the definitions given earlier:

$$\frac{2}{\Delta t}(\zeta^{n+\frac{1}{2}}_{j,k} - \zeta^n_{j,k}) + \left[(h_{j+\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}} + \zeta^n_{j+1,k} + \zeta^n_{j,k})u^{n+\frac{1}{2}}_{j+\frac{1}{2},k}\right.$$

$$\left. - (h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j-\frac{1}{2},k-\frac{1}{2}} + \zeta^n_{j-1,k} + \zeta^n_{j,k})u^{n+\frac{1}{2}}_{j-\frac{1}{2},k}\right] \frac{1}{2\Delta x}$$

$$+ \left[(h_{j+\frac{1}{2},k+\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}} + \zeta^n_{j,k+1} + \zeta^n_{j,k})v^n_{j,k+\frac{1}{2}}\right.$$

$$\left. - (h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k-\frac{1}{2}} + \zeta^n_{j,k} + \zeta^n_{j,k-1})v^n_{j,k-\frac{1}{2}}\right] \frac{1}{2\Delta x} = S$$

which can be rewritten as

$$-r_{j-\frac{1}{2}}u^{n+\frac{1}{2}}_{j-\frac{1}{2},k} + \zeta^{n+\frac{1}{2}}_{j,k} + r_{j+\frac{1}{2}}u^{n+\frac{1}{2}}_{j+\frac{1}{2},k} = A^n_j \qquad \text{(A)}$$

where: $$r_{j-\frac{1}{2}} = (h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j-\frac{1}{2},k-\frac{1}{2}} + \zeta^n_{j-1,k} + \zeta^n_{j,k}) \frac{\Delta t}{4\Delta x}$$

$$r_{j+\frac{1}{2}} = (h_{j+\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}} + \zeta^n_{j+1,k} + \zeta^n_{j,k}) \frac{\Delta t}{4\Delta x}$$

$$A_j^n = {}^{n}_{j,k} + (h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k-\frac{1}{2}} + \zeta^n_{j,k} + \zeta^n_{j,k-1})v^n_{j,k-\frac{1}{2}}(\frac{\Delta t}{4\Delta x})$$

$$- (h_{j+\frac{1}{2},k+\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}} + \zeta^n_{j,k+1} + \zeta^n_{j,k})v^n_{j,k+\frac{1}{2}}(\frac{\Delta t}{4\Delta x})$$

$$+ S\ (\frac{\Delta t}{2})$$

Expanding the momentum equation the same manner yields:

$$\frac{1}{\Delta t}\left(u^{n+\frac{1}{2}}_{j+\frac{1}{2},k} - u^{n-\frac{1}{2}}_{j+\frac{1}{2},k}\right) - f\bar{\bar{v}} + \left(u^{n-\frac{1}{2}}_{j+\frac{3}{2},k} - u^{n-\frac{1}{2}}_{j-\frac{1}{2},k}\right) u^{n+\frac{1}{2}}_{j+\frac{1}{2},k}\ \frac{1}{2\Delta x}$$

$$+ \left(u^{n-\frac{1}{2}}_{j+\frac{1}{2},k+1} - u^{n-\frac{1}{2}}_{j+\frac{1}{2},k-1}\right)\frac{\bar{\bar{v}}}{2\Delta x} + \left(\zeta^{n+\frac{1}{2}}_{j+1,k} - \zeta^{n+\frac{1}{2}}_{j,k} + \zeta^{n-\frac{1}{2}}_{j+1,k} - \zeta^{n-\frac{1}{2}}_{j,k}\right)\frac{g}{2\Delta x}$$

$$+ \frac{\left(\frac{g}{2}\right)\left(u^{n+\frac{1}{2}}_{j+\frac{1}{2},k} + u^{n-\frac{1}{2}}_{j+\frac{1}{2},k}\right)\left[\left(u^{n-\frac{1}{2}}_{j+\frac{1}{2},k}\right)^2 + (\bar{\bar{v}})^2\right]^{\frac{1}{2}}}{(\bar{h}^y + \bar{\zeta}^x)(\bar{C}^x)^2} - \frac{1}{\rho(\bar{h}^y + \bar{\zeta}^x)}\ \tau^s_x$$

$$+ \frac{u^{n+\frac{1}{2}}_{j+\frac{1}{2},k}S}{2(\bar{h}^y + \bar{\zeta}^x)} + \frac{u^{n-\frac{1}{2}}_{j+\frac{1}{2},k}S}{2(\bar{h}^y + \bar{\zeta}^x)} = 0$$

which may be written as:

$$-r_j\zeta^{n+\frac{1}{2}}_{j,k} + r'_{j+\frac{1}{2}}u^{n+\frac{1}{2}}_{j+\frac{1}{2},k} + r_{j+1}\zeta^{n+\frac{1}{2}}_{j+1,k} = B^n_{j+\frac{1}{2},k} \qquad \text{(B)}$$

where

$$r_j = r_{j+1} = \frac{g\Delta t}{2\Delta x}$$

$$r'_{j+\frac{1}{2}} = 1 + \frac{t}{2\Delta x}\left(u^{n-\frac{1}{2}}_{j+\frac{3}{2},k} - u^{n-\frac{1}{2}}_{j-\frac{1}{2},k}\right) + \frac{\frac{g\Delta t}{2}\left[\left(u^{n-\frac{1}{2}}_{j+\frac{1}{2},k}\right)^2 + (\bar{\bar{v}})^2\right]^{\frac{1}{2}}}{(\bar{h}^y + \bar{\zeta}^x)(\bar{C}^x)} + \frac{S\Delta t}{2(\bar{h}^y + \bar{\zeta}^x)}$$

$$B^n_{j+\frac{1}{2},k} = u^{n-\frac{1}{2}}_{j+\frac{1}{2},k} + \left[f\Delta t - \frac{\Delta t}{2\Delta x}\left(u^{n-\frac{1}{2}}_{j+\frac{1}{2},k+1} - u^{n-\frac{1}{2}}_{j+\frac{1}{2},k-1}\right)\right]\bar{\bar{v}}$$

$$- g \frac{\Delta t}{2\Delta x}\left(\zeta^{n-\frac{1}{2}}_{j+1,k} - \zeta^{n-\frac{1}{2}}_{j,k}\right) - \frac{\frac{g\Delta t}{2} u^{n-\frac{1}{2}}_{j+\frac{1}{2},k}\left[\left(u^{n-\frac{1}{2}}_{j+\frac{1}{2},k}\right)^2 + (\bar{\bar{v}})^2\right]^{\frac{1}{2}}}{(\bar{h}^y + \bar{\zeta}^x)(\bar{C}^x)^2}$$

$$+ \frac{1}{\rho(\bar{h}^y + \bar{\zeta}^x)} \tau^s_x - \frac{u^{n-\frac{1}{2}}_{j+\frac{1}{2}} S\Delta t}{2(\bar{h}^y + \bar{\zeta}^x)}$$

Equations A & B can be solved alternatively once conditions are known at both ends of a row. The boundaries may be specified as open or closed and respectively values of velocity or water levels can be used at input. Assuming that on the left side of the grid the boundary is open then the water level is known and equation (B) reduces to:

$$u^{n+\frac{1}{2}}_{J+\frac{1}{2}} = -R_J\zeta^{n+\frac{1}{2}}_{J+1} + S_J \qquad \text{(C)}$$

where J = 1 for left boundary.

$$R_J = \frac{r_{J+1}}{r'_{J+\frac{1}{2}}}$$

$$S_J = \frac{B^n_{J+\frac{1}{2}} + r_J \, BWL}{r'_{J+\frac{1}{2}}}$$

BWL = Boundary water level.

In the above equation both R_J and S_J are known so that the unknown velocity is defined in terms of the unknown water elevation next to it on the grid. This unknown water elevation may be found by substituting equation (C) into equation (A) as follows:

$$-r_{J+\frac{1}{2}}\left[-R_J\zeta^{n+\frac{1}{2}}_{J+1} + S_J\right] + \zeta^{n+\frac{1}{2}}_{J+1} + r_{J+\frac{3}{2}} \, u^{n+\frac{1}{2}}_{J+\frac{3}{2}} = A^n_{J+1}$$

or

$$\zeta^{n+\frac{1}{2}}_{J+1} = -P_{J+1} \, u^{n+\frac{1}{2}}_{J+\frac{3}{2}} + Q_{J+1} \qquad \text{(D)}$$

where

$$P_{J+1} = \frac{r_{J+3/2}}{1 + r_{J+1/2} R_J}$$

$$Q_{J+1} = \frac{A^n_{J+1} + r_{J+1/2} S_J}{1 + r_{J+1/2} R_J}$$

Thus the water level is now defined in terms of the unknown velocity to its right on the grid. By repetitively substituting into equations (A) and (B) the velocities U and water levels ζ may be defined in terms of the unknown ζ and U to their right on a row by the two following generalized equations:

$$\zeta^{n+1/2}_j = -P_j u^{n+1/2}_{j+1/2} + Q_j \tag{E}$$

$$u^{n+1/2}_{j-1/2} = -R_{j-1} \zeta^{n+1/2}_j + S_{j-1} \tag{F}$$

$$P_j = \frac{r_{j+1/2}}{1 + r_{j-1/2} R_{j-1}}$$

$$Q_j = \frac{A^n_j + r_{j-1/2} S_{j-1}}{1 + r_{j-1/2} R_{j-1}}$$

$$R_j = \frac{r_{j+1}}{r'_{j+1/2} + r_j P_j}$$

$$S_j = \frac{B^n_{j+1/2} + r_j Q_j}{r'_{j+1/2} + r_j P_j}$$

The recursion factors P, Q, R and S may be calculated in succession starting $j = 1$ and proceeding to the right hand boundary. Assuming the right hand boundary is closed then it is known that the velocity across it is zero. Equation (E) may then be used to calculate the ζ to the left of the boundary since P, Q, and U are known. The rest of the velocities and water levels may be calculated from right to left across the grid by alternately using equation (F) and (E). Similar

equations may be developed if different boundary conditions are picked along the left and right edges of the grid. The procedure is repeated for each row of the grid to give the U velocity and water level ζ for every point at time level $n+\frac{1}{2}$.

To solve for the pollutant concentrations at time step $n+\frac{1}{2}$, mass transport equation 1 must be expanded as follows for component i

$$
\begin{aligned}
&[P^{n+\frac{1}{2}}_{j,k;i}(h_{j-\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j+\frac{1}{2},k+\frac{1}{2}} + 4\zeta^{n+\frac{1}{2}}_{j,k}) \\
&-P^{n}_{j,k;i}(h_{j-\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j+\frac{1}{2},k+\frac{1}{2}} + 4\zeta^{n}_{j,k})]\ \frac{1}{2\Delta t} \\
&-[(\zeta^{n}_{j-1,k} + \zeta^{n}_{j,k} + h_{j-\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}})u^{n+\frac{1}{2}}_{j-\frac{1}{2},k}(P^{n+\frac{1}{2}}_{j-1,k;i} + P^{n+\frac{1}{2}}_{j,k;i}) \\
&-(\zeta^{n}_{j,k} + \zeta^{n}_{j+1,k} + h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j+\frac{1}{2},k+\frac{1}{2}})u^{n+\frac{1}{2}}_{j+\frac{1}{2},k}(P^{n+\frac{1}{2}}_{j,k;i} + P^{n+\frac{1}{2}}_{j+1,k;i})](\frac{1}{4\Delta x}) \\
&-[(\zeta^{n}_{j,k-1} + \zeta^{n}_{j,k} + h_{j-\frac{1}{2},k-\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}})v^{n}_{j,k-\frac{1}{2}}(P^{n}_{j,k-1;i} + P^{n}_{j,k;i}) \\
&-(\zeta^{n}_{j,k} + \zeta^{n}_{j,k+1} + h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k+\frac{1}{2}})v^{n}_{j,k+\frac{1}{2}}(P^{n}_{j,k+1;i} + P^{n}_{j,k;i})](\frac{1}{4\Delta x}) \\
&+[(\zeta^{n+\frac{1}{2}}_{j-1,k} + \zeta^{n+\frac{1}{2}}_{j,k} + h_{j-\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}})D^{n+\frac{1}{2}}_{x_{j-\frac{1}{2},k}}(P^{n+\frac{1}{2}}_{j,k;i} - P^{n+\frac{1}{2}}_{j-1,k;i}) \\
&-(\zeta^{n+\frac{1}{2}}_{j,k}+\zeta^{n+\frac{1}{2}}_{j+1,k}+h_{j+\frac{1}{2},k-\frac{1}{2}}+h_{j+\frac{1}{2},k+\frac{1}{2}})D^{n+\frac{1}{2}}_{x_{j+\frac{1}{2},k}}(P^{n+\frac{1}{2}}_{j+1,k;i}-P^{n+\frac{1}{2}}_{j,k;i})]\left[\frac{1}{2(\Delta x)^2}\right] \\
&+[(\zeta^{n}_{j,k-1} + \zeta^{n}_{j,k} + h_{j-\frac{1}{2},k-\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}})D^{n}_{y_{j,k-\frac{1}{2}}}(P^{n}_{j,k;i} - P^{n}_{j,k-1;i}) \\
&-(\zeta^{n}_{j,k}+\zeta^{n}_{j,k+1}+h_{j-\frac{1}{2},k+\frac{1}{2}}+h_{j+\frac{1}{2},k+\frac{1}{2}})D^{n}_{y_{j,k+\frac{1}{2}}}(P^{n}_{j,k+1;i}-P^{n}_{j,k;i}]\left[\frac{1}{2(\Delta x)^2}\right] \\
&+\sum_{\ell=1}^{i-1}(h_{j+\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j-\frac{1}{2},k-\frac{1}{2}} + 4\zeta^{n+\frac{1}{2}}_{j,k})\frac{K_{i\ell}P^{n+\frac{1}{2}}_{j,k;\ell}}{4}\alpha_i \\
&+[(h_{j+\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j-\frac{1}{2},k-\frac{1}{2}} + 4\zeta^{n+\frac{1}{2}}_{j,k})K_{ii}P^{n+\frac{1}{2}}_{j,k;i}
\end{aligned}
$$

$$+(h_{j+\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j-\frac{1}{2},k-\frac{1}{2}} + 4\zeta^{n}_{j,k})K_{ii}P^{n}_{j,k;i}](\tfrac{1}{8})$$

$$+\sum_{\ell=i+1}^{\ell_{max}}(h_{j+\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j-\frac{1}{2},k-\frac{1}{2}} + 4\zeta^{n}_{j,k})\frac{K_{i\ell}P^{n}_{j,k;\ell}}{4}\beta_{i}$$

$$+(h_{j+\frac{1}{2},k+\frac{1}{2}} + h_{j+\frac{1}{2},k-\frac{1}{2}} + h_{j-\frac{1}{2},k+\frac{1}{2}} + h_{j-\frac{1}{2},k-\frac{1}{2}} + 4\zeta^{n}_{j,k})\frac{S^{n}_{j,k;i}}{4} = 0$$

The above equation may be rewritten in terms of the unknown concentrations at time level $n+\frac{1}{2}$ as:

$$a_{j}P^{n+\frac{1}{2}}_{j-1,k;i} + b_{j}P^{n+\frac{1}{2}}_{j,k;i} + c_{j}P^{n+\frac{1}{2}}_{j+1,k;i} = D_{j} \qquad \text{(H)}$$

or for a given row and time level and constituent

$$a_{j}P_{j-1} + b_{j}P_{j} + C_{j}P_{j+1} + D_{j} \qquad \text{(I)}$$

Beginning at the left side of the grid as before either the boundary concentration is known if the boundary is open or the boundary is closed in which case $a_{J} = 0$. Assuming the latter case equation (I) reduces for $j = J$ to

$$b_{J}P_{J} + c_{J}P_{J+1} = D_{J}$$

or

$$P_{J} = E_{J+1}P_{J+1} + Q_{J+1} \qquad \text{(J)}$$

where

$$E_{J+1} = -\frac{c_{J}}{b_{J}}\ ; \quad Q_{J+1} = \frac{D_{J}}{b_{J}}$$

For the next point ($j = J+1$) across the grid equation (I) gives

$$a_{J+1}P_{J} + b_{J+1}P_{J+1} + c_{J+1}P_{J+2} = D_{J+1}$$

or substituting equation (J) for P_{J} and rearranging

$$P_{J+1} = E_{J+2}P_{J+2} + Q_{J+2}$$

where

$$E_{J+2} = -\frac{c_{J+1}}{b_{J+1} + a_{J+1}E_{J+1}} \; ; \quad Q_{J+2} = \frac{D_{J+1} - a_{J+1}Q_{J+1}}{b_{J+1} + a_{J+1}E_{J+1}}$$

or in general $(J = j)$

$$P_j = E_{j+1}P_{j+1} + Q_{j+1} \qquad \text{(K)}$$

where

$$E_{j+1} = -\frac{c_j}{b_j + a_jE_j}$$

$$Q_{j+1} = \frac{D_j - a_jQ_j}{b_j + a_jE_j}$$

Thus each concentration on a row may be defined in terms of two determinable constants and the unknown concentration immediately to its right on the row. Hence if the right hand boundary value is known the other concentrations on the row may be determined by repetitive use of equation (K) from right to left. If the boundary is open then the boundary value must be input and the solution is trivial. If it is assumed that the boundary is closed at $(j = M)$ then equation (I) reduces to:

$$a_MP_{M-1} + b_MP_M = D_M$$

since there is no diffusion or advection across the boundary. (i.e. $C_M = 0$). The above equation may be solved for P_{M-1} to give

$$P_{M-1} = -\frac{b_M}{a_M}P_M + \frac{D_M}{a_M} \qquad \text{(L)}$$

However, the general recursion equation (K) for $j = M-1$ yields

$$P_{M-1} = E_MP_M + Q_M \qquad \text{(M)}$$

Substituting equation (M) into equation (L) yields

$$E_MP_M + Q_M = -\frac{b_M}{a_M}P_M + \frac{D_M}{a_M}$$

solving for P_M yields

$$P_M = \frac{D_M - a_M Q_M}{b_M + a_M E_M} = Q_{M+1}$$

Consequently the rightmost concentration next to a boundary may be found and then the other concentrations on that row may be found by using equation (K) repetitively from right to left.

An analogous set of equations may be developed for the second set of equations for the second half time step and are solved moving up and down the columns of the grid.

HAMILTON HARBOUR STUDY

section F

bottom fauna & microbiology

HAMILTON HARBOUR STUDY
SECTION F
BOTTOM FAUNA AND MICROBIOLOGY

SUMMARY

THE GENERAL BENTHIC MACROINVERTEBRATE COMMUNITY OF HAMILTON HARBOUR HAS CHANGED ONLY SLIGHTLY IN THE PAST EIGHT OR NINE YEARS. THE INVERTEBRATE DENSITY THROUGHOUT MOST OF THE HARBOUR (EXCLUDING THE SOUTH-EAST CORNER HAS INCREASED, POSSIBLY INDICATING A SLIGHT IMPROVEMENT IN GENERAL BIOLOGICAL CONDITIONS. THE 1973 BOTTOM FAUNA INVESTIGATION INDICATES THAT BIOLOGICAL CONDITIONS IN THE SOUTH-EAST CORNER OF THE HARBOUR ARE LESS FAVOURABLE NOW THAN THEY WERE IN 1964.

BACTERIOLOGICAL LEVELS IN 1972 WERE GENERALLY TOO HIGH TO PERMIT TOTAL BODY CONTACT RECREATION. NO STATISTICAL TREND WAS OBSERVED IN THE BACTERIOLOGICAL LEVELS FROM 1970 TO 1972.

HAMILTON HARBOUR

BOTTOM FAUNA AND MICROBIOLOGY

INTRODUCTION

In 1964 and 1965, a biological survey of Hamilton Bay was carried out by the Ontario Water Resources Commission. The results of that study, published in the report entitled "Biological Survey Of The Hamilton Bay And Adjacent Lake Ontario: 1964-65", revealed that the benthic macroinvertebrate community of the Harbour had been substantially altered by the waste discharges.

In 1972 and 1973, the bottom fauna was again investigated as part of the over-all Hamilton Harbour Study. The main purpose of this bottom invertebrate investigation was to find out whether or not the biological conditions had changed since the work of Johnson in 1964-65.

The bacteriological data for 1970 and 1971 were obtained from the Annual Reports of the Department of Municipal Laboratories in Hamilton. The 1972 bacteriological data were obtained by the Ontario Ministry of the Environment.

METHODOLOGY BOTTOM FAUNA

The bottom invertebrate population was evaluated during two sampling periods. In mid-August, 1972, a total of 17 locations were sampled by obtaining one mud sample, using a 9" x 9" Eckman dredge, from each location. The 17 locations corresponded to those that were established for the physical-chemical modelling study (see Figure 1).

In early April, 1973, an additional 22 locations were sampled using a 6" x 6" Eckman dredge. These 22 locations, illustrated in Figure 2, correspond to approximately every second station sampled by Johnson in 1964.

The invertebrates from all samples collected in both 1972 and 1973 were separated from the sediment using a brass screen with an aperture size of 0.65 mm. The organisms were placed in ethanol (70%-90%) and later identified in the laboratory. All the samples are presently retained at the Water Quality Branch, Ministry of Environment.

DISCUSSION BOTTOM FAUNA

The benthic population throughout most of Hamilton Harbour can best be described as a community with a low diversity and a high density. With the exception of the odd midge and fingernail clam, the benthic population is restricted to one invertebrate family, namely tubificidae, commonly known as the "sludgeworm" family. In the south-east corner of the Bay, toxic conditions were evident as six sediment samples were void of macroinvertebrates.

Comparisons of the 1972-73 results with the data from 1964-65 reveal that there have been changes in the past eight years. Firstly, the toxic zone appears to have changed (see Figure 3); in 1964, the toxic zone included the Ottawa Street Slip, as well as an area extending from this inlet out into the Harbour. The 1972-73 data indicated that the toxic area now encompasses a larger area in the south-east corner of the Bay (Figure 3). The reason for this change in the location of the toxic area probably relates to the fact that prior to 1964, raw sewage was discharged to the Ottawa Street Slip; since the development of the municipal sewage treatment plant in 1964, treated sewage has been discharged to the south-east corner of the Harbour.

Secondly, the density of bottom invertebrates throughout most of the Bay (excluding the south-east corner) appears to be significantly increased since 1964 (Figure 3). In 1964, there was only a small area, extending into the Harbour from the Lake Ontario outlet, where oligochaete densities exceeded 1000 per square foot. Much of the Harbour contained less than 100 oligochaete worms per square foot. The 1972-73 work revealed that worm densities now exceed 1000 throughout a large part of the Harbour, and very little of the Harbour area contains fewer than 100 per square foot. This density change is expected to be a result of one of two factors; either there has been an increase in the amount of organic material settling to the bottom which has increased the food supply for the sludgeworms, or the degree of toxicity has decreased, enabling the worm population to expand and make fuller use of the existing food supply. The cause of this change must really be defined before one can say whether the density increase indicates an improvement or deterioration in the general biological condition of the Harbour. While the amount of pertinent information required to answer this question is quite limited, the existing information would tend to indicate that the increased worm density is more likely a result of a reduction in toxins. During the past seven or eight years, parameters which can be used to provide an indication of organic "fallout" (e.g. total phosphorus, nitrogen, chlorophyll a) do not indicate any substantial increase in the amount of organics settling to the bottom. On the other hand,

there was a very definite decrease in the concentration of ammonia in 1972 as a result of improvements in industrial discharges. It therefore appears more likely that the increase in bottom invertebrate density is a result of reduced toxicity and hence is indicative of a healthier biological environment.

Thirdly, the 1972-73 data was compared with the 1964-65 data to see if there has been any change in the benthic community composition, and the diversity of taxa. The 1972-73 survey revealed that not unlike the conditions of eight years previous, the community diversity was very low; at the large majority of stations, only sludgeworms were found. Even the variety of species within the sludgeworm community was limited; Johnson reported that "only two species, Limnodrilus hoffmeisteri and Tubifex tubifex, were abundant" and this same statement applies to the existing benthic community. However, while the community structure and species diversity is basically similar to what it was eight to nine years ago, it appears that there may have been a slight increase in diversity. In 1964, five of the 46 samples collected contained organisms other than oligochaete worms; in 1972-73, seven of the 39 samples contained organisms other than worms (see Figure 4). Also, in the 1964 samples, the only two groups of live organisms found were oligochaetes and midges; in 1972-73, as well as finding oligochaetes and midges, live fingernail clams were found at five of the 39 stations. These apparent slight changes in community structure would indicate that the aquatic environment is perhaps suitable for a larger variety of organisms than it was eight or nine years ago.

DISCUSSION MICROBIOLOGY

The sampling station locations are shown on Figure 1 and the bacteriological water quality data for the 1972 surveys by the Ontario Ministry of the Environment appear in Table 1 (total coliform), Table 2 (fecal coliform) and Table 3 (enterococci).

The results indicate poor bacteriological water quality throughout Hamilton Harbour, in reference to the criteria for total body contact recreation which states "where ingestion is probable, recreational water can be considered impaired when the coliform, fecal coliform and/or enterococcus geometric mean density exceeds 1000, 100 and/or 20 per 100 ml respectively, in a series of at least ten samples per month, including samples collected during weekend periods".

The regions of highest levels of bacterial contamination occur near the sewage treatment plant outfall (location 20), along

the Burlington Skyway (location 251) and near the principle industrial outfalls (location 256, 259 and 262), while the regions of least contamination extends from the deep locations (258 and 254) to the north shore (260, 259 and 253). The water pollution surveys of the Hamilton Municipal Laboratories in 1970 and 1971 show similar patterns for surface samples collected from March to December.

Geometric means of fecal coliforms/100 ml for years 1970, 1971 and 1972 are presented in Table 4. The results of 1970 and 1971 are taken from the Annual Reports of the Department of Municipal Laboratories in Hamilton, 1972 data are those of this study taken at 1.5 m depth level. Only the stations similarly located in both studies were chosen for comparison and the period from July 21 to November 15 of each year, where enough data exist were compared.

From Table 4 it is evident that some change in the fecal coliform/100 ml counts from year to year appears, with the counts for 1971 apparently being the lowest. The significance of the differences between years was tested statistically with a t-test and the results appear in Table 5. The means are not significantly different at the 95% significance level. Therefore, no conclusion about the change in the bacteriological quality of water in the Hamilton Harbour during years 1970-72 can be made.

Coliform and fecal coliform data for the period 1960 to 1970 are presented in the Hamilton Municipal Laboratory, 1970 Annual Report. The median values for the seven sampling locations in the period 1960-5 are generally higher than those in the period 1965-70. However the comparisons of survey results from any two successive years may not support this trend as the medians fluctuate a great deal. The Hamilton Municipal Laboratories state that with the exception of one location the medians in 1970 are substantially lower than 1969. It appears that bacti levels are generally decreasing over the years.

TABLE 1: Hamilton Harbour Survey 1972. Total Coliform /100 ml.

Station Number	Depth in Meters from Surface 0.2	1.5	3.0	4.5	6.0	9.0	12.0
15	121,000	11,918 (3)			9,749 (3)		
20		6,084 (14)	8,632 (8)	13,349 (12)	55,000		
251	4,100	9,804 (4)		2,100		140,000	500
252		1,151 (12)	2,056 (6)	500	2,600		
253	900	1,776 (3)	16,000	1,500			
254		1,813 (4)	200		100	2,898 (2)	
255	5,300	1,433 (4)		900	1,430 (3)		
256	2,200	5,409 (15)	12,479 (3)	3,420 (3)	3,293 (7)		
257		711 (13)		2,345 (4)	871 (7)	343 (3)	
258		795 (15)		1,508 (4)	235 (3)	1,193 (3)	1,816 (2)
259		8,814 (4)	40,000			13,229 (2)	
260	16,000	9,061 (3)			10,000	4,100	
261	1,700	13,675 (2)			55,000	2,400	
262	6,000	9,726 (12)	2,310 (3)	7,462 (10)			
263		18,882 (3)		45,000	4,900		
265	34,000	4,165 (12)	100	2,181 (4)	1,280 (6)		
269	2,700	657 (16)		559 (5)	1,333 (8)	1,520 (2)	

When more than one sample was taken at any location, the geometric mean is reported and the number of samples is recorded in parenthesis.

TABLE 2: Hamilton Harbour Survey 1972 - Fecal Coliform/100 ml.

Station Number	Depth in Meters from Surface 0.2	1.5	3.0	4.5	6.0	9.0	12.0
15	390	234 (3)			334 (3)		
20		319 (14)	632 (7)	32 (2)			
251	200	163 (4)		80		1,400	
252		109 (9)	49 (7)				
253	40	20 (3)	180	20			
254		64 (3)	20			110 (2)	
255	530	50 (4)		10	127 (2)		
256	30	488 (14)	1,221 (3)	440 (2)	183 (6)		
257		42 (10)		37 (2)	43 (6)		
258		79 (14)	70	68 (4)	57 (2)	118 (3)	134 (3)
259		170 (5)	180			185 (3)	
260		30	87 (3)		120	50	
261	90	245 (2)			210	330	
262		494 (14)	565 (2)	620 (10)			
263		62 (3)		400	70		
265	240	97 (10)	30	69 (4)	195 (4)	10	
269		92 (13)	310	66 (3)	217 (5)	850	

When more than one sample was taken at any location, the geometric mean is reported and the number of samples is recorded in parenthesis.

TABLE 3: Hamilton Harbour Survey, 1972. Enterococci/100 ml.

Station Number	Depth in Meters from Surface 0.2	1.5	3.0	4.5	6.0	9.0	12.0
15	7	11 (3)			34 (3)		
20		77 (14)	159 (8)	28 (2)			
251	20	49 (4)		6		216	7
252		9 (10)	11 (8)		3		
253	1	6 (2)	5	1			
254		4 (3)				15 (2)	
255	14	7 (4)			10 (3)		
256	2	46 (13)	94 (3)	3 (3)	51 (6)		
257		4 (12)		3 (3)	5 (7)	2 (3)	
258		7 (12)	4	4 (4)	4 (3)	9 (4)	13 (3)
259		14 (3)	1			15 (2)	2
260		2 (3)			2		
261	5	15 (2)			7	3	
262	21	30 (13)	16 (2)	68 (10)	12		
263		3 (2)		21			
265	3	7 (12)		7 (3)	15 (6)	1	
269	8	7 (12)	16	7 (3)	17 (7)	30 (2)	

When more than one sample was taken at any location, the geometric mean is reported and the number of samples is recorded in parenthesis.

TABLE 4: Hamilton Harbour Survey. Geometrical Means of Fecal Coliforms/100 ml

Station Number	Year 1970	Year 1971	Year 1972
20	831 (8)	246 (5)	319 (14)
256	1026 (7)	359 (5)	488 (14)
257	32 (9)	4 (5)	42 (10)
258	37 (8)	42 (5)	79 (14)
262	355 (8)	286 (5)	494 (14)
265	51 (8)	12 (5)	97 (10)
269	88 (8)	42 (5)	92 (13)

In parenthesis are the number of samples used for calculation of the mean. 1970 and 1971 data are from water pollution surveys of Hamilton Municipal Laboratories, 1972 data are from this work at the depth level of 1.5 m.

TABLE 5: Hamilton Harbour Survey. t-Test of Fecal Coliforms/100 ml for 1970-1972

Station	Comparison Between Means for Years		
	1970-1971	1970-1972	1971-1972
Number	D.F. t	D.F. t	D.F. t
20	11 0.919	20 0.446	17 1.461
256	10 0.738	19 1.037	17 1.408
257	12 1.311	17 0.533	13 1.731
258	11 0.978	20 0.356	17 1.269
262	11 1.118	20 0.238	17 1.036
265	11 0.948	16 1.308	13 1.200
269	11 0.866	19 0.644	16 0.031

Degree of Freedom D.F.=$n_1 + n_2 - 2$, where n_1 and n_2 are numbers of observations in the years compared.

At 95% significance level there is not a significant difference between individual years.

F 10

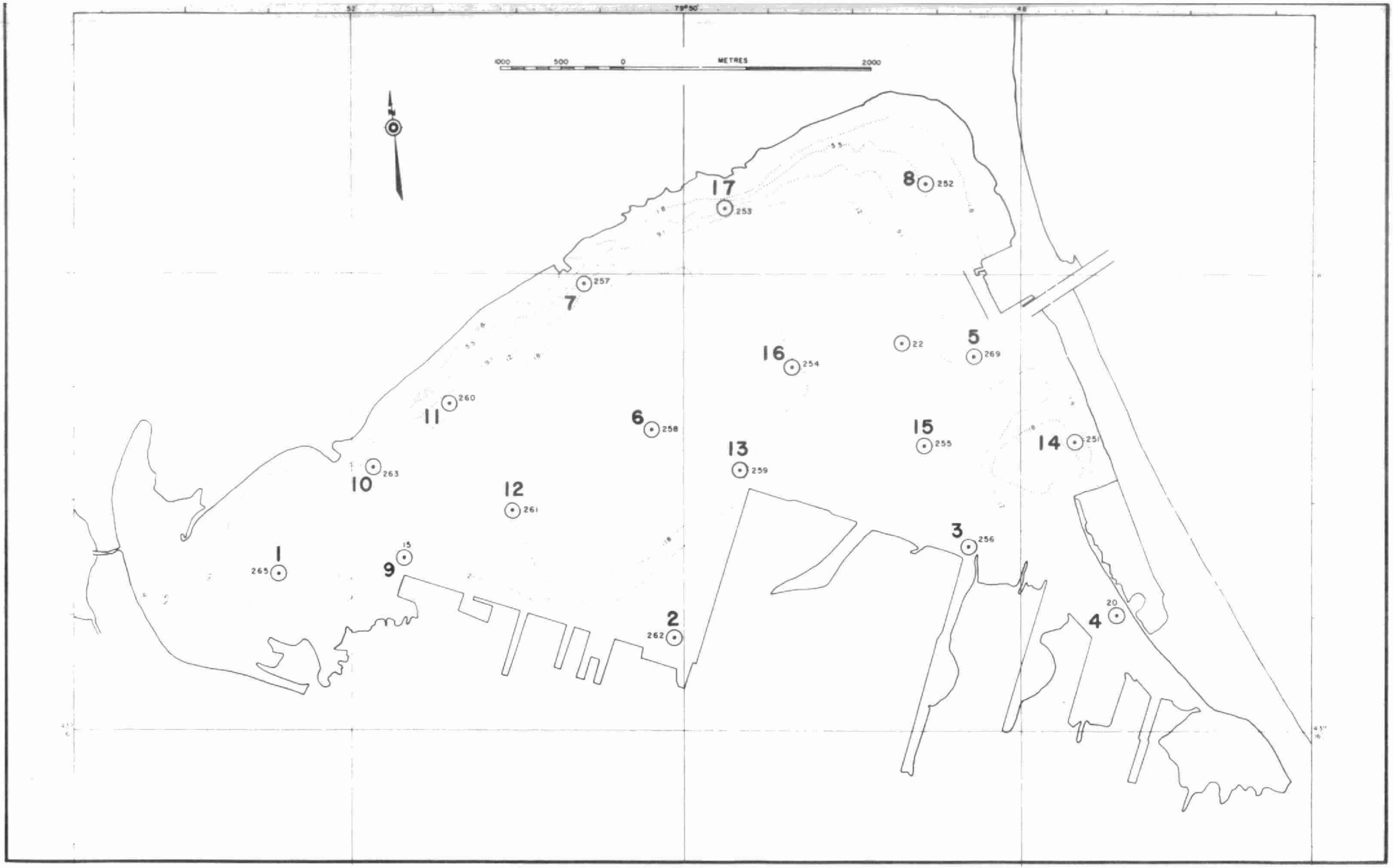


FIGURE 1 : SAMPLING LOCATIONS AUGUST, 1972

Figure 2: Sampling Locations April, 1973

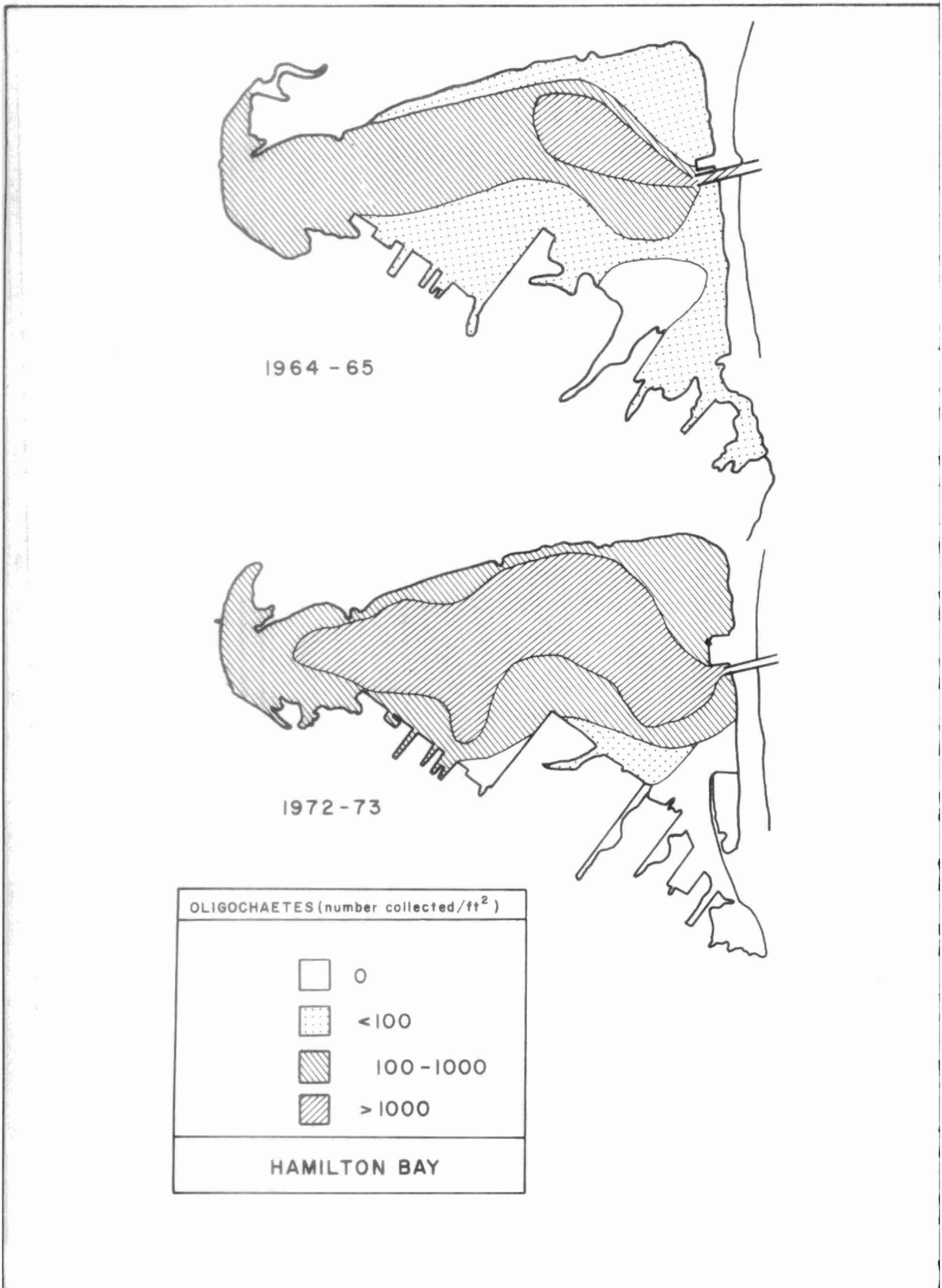


Figure 3: Worm (Oligochaete) Densities, Number of Organisms/ft^2

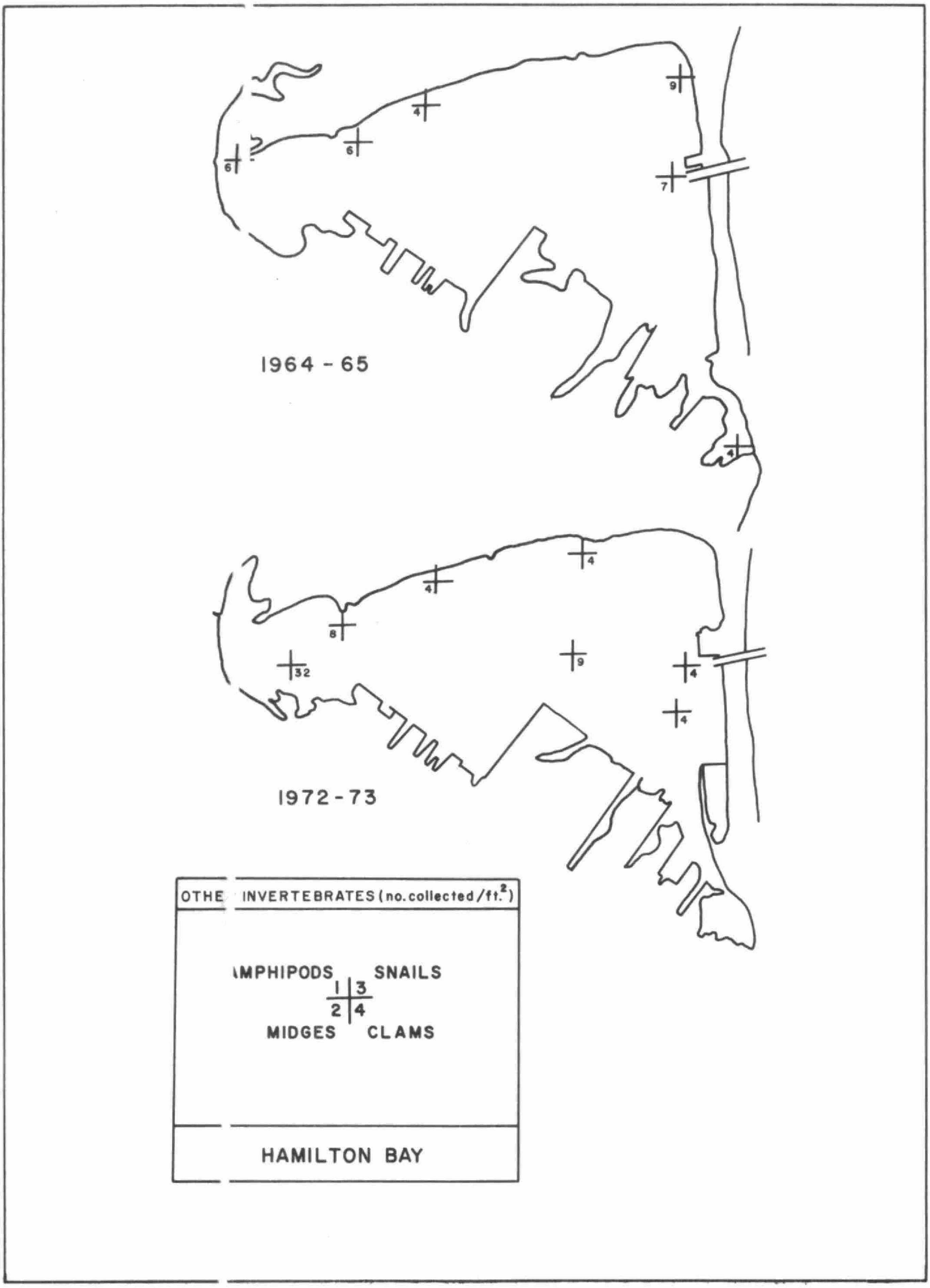


Figure 4: Other Invertebrates, Number/ft^2

HAMILTON HARBOUR STUDY

section G

heavy metals
& pesticides

HAMILTON HARBOUR

HEAVY METALS AND PESTICIDES

INTRODUCTION

As part of the water quality surveys in Hamilton Harbour, bottom sediments and fish were collected for heavy metal and pesticide analyses. The purpose of this survey was to establish existing levels in the harbour and identify any regions of accumulations substantially greater than average.

Fish were caught by the Ministry of Natural Resources with gill nets at three locations (Figure 1). The Ministry of the Environment analysed the fish muscle for polychlorinated biphenyls and the Provincial Pesticide Residue Testing Laboratory analysed fish tissue puree for mercury and pesticides.

Bottom sediments were collected at eleven locations in the harbour. These samples were a composite of three bottom sediment grabs collected in an area of approximately three meters square. The dredged material was skimmed from the top three centimetres. The sediments were analysed by the Ontario Ministry of the Environment for PCB, lead, chromium, cadmium, mercury and iron.

RESULTS

The locations of the bottom sediment samples appear in Figure 1 with the results of analyses recorded in Table 1. In general, it is observed that the sediments in the harbour contain high concentrations of heavy metals with the worst locations near Randles Reef and the municipal waste treatment plant outfall. The levels of mercury in fish puree, however, as shown in Table 3, are generally low and not significantly different to concentrations normally accepted as "background." Fish with mercury levels of to 0.5 ppm are considered suitable as human food. It is noted that one white bass at Station F1 contained mercury at this threshold. In relation to the results from the other sediment analyses, there is a lack of scientific understanding of conditions which favour uptake of materials such as PCB, lead, chromium, cadmium and iron, into the aquatic food chain or of the significance of such accumulations to the biota.

For comparison purposes, the concentrations of cadmium, chromium and lead at eleven stations in the Lake Erie western basin are shown below:

	Cadmium (ppm)	Chromium (ppm)	Lead (ppm)
Average	5.6	177	85.9
Maximum	13.7	362	173
Minimum	2.2	50	30

The levels of PCB in fish are contained in both Tables 2 and 4. In the absence of a standard for the maximum permissible value for PCB in fish food for humans, the fish in Hamilton Harbour could not be rejected on this basis. Some authorities, however, consider that the maximum permissible content for PCB should be the same as for DDT which has been set at 5 ppm. In this context, it is noted that some of the predator fish or those fish with high body fat have PCB content approaching 12 ppm. On the other hand, there are other authorities who believe that no standard should be set until more is known about the biological impact of PCB's in its various forms.

In Table 4, it is encouraging to note the low values for DDT as compared to the breakdown products of DDE and DDD. This suggests that recent DDT pollution is absent. The concentrations of other pesticides are considered as normal background values for a body of water abutting an area of high commercial and industrial activity.

TABLE 1 ANALYSES OF SEDIMENT

July 19, 1972

Station	264	15	262	257	255	256	269	1030	267	20	268
PCB (ppm)	.80	2.0	3.0	.58	.05	.17	1.3	.22	.26	.66	10.1
Lead (ppm)	100	420	930	170	25	55	140	60	60	80	340
Chromium (ppm)	40	210	150	120	27	47	97	13	41	43	295
Cadmium (ppm)	---	---	18.5	8	---	5.0	6	---	---	5.0	---
Mercury (ppm)	---	---	1.7	.81	---	.21	.7	---	---	.4	---
Iron %	2.8	6.1	9.4	4.4	1.6	3.3	3.8	1.4	2.3	2.4	3.8

TABLE 2 PCB IN FISH MUSCLE

August 14, 15 16, 1972

Report from Ontario Ministry of the Environment Laboratory

Station F1 - No Fish Caught

	Fish Species	# Examined	PCB (ppm)			
			Max	Min	Avg	Median
Station F2	Carp	3	5.7	0.16	3.72	5.3
	White Bass	10	5.6	1.0	2.4	2.15
	White Sucker	1	0.4	0.4	0.4	0.4
	Gizzard Shad	4	2.0	1.1	1.6	1.65
Station F3	Carp	6	11.6	0.24	3.36	2.35
	Shad	4	3.1	0.91	2.38	2.75

TABLE 3 MERCURY IN FISH PUREE (PPM)

August 14, 15, 16, 1972

Report from the Provincial Pesticide Residue Testing Laboratory

Station F1 - No Fish Caught

	Fish Species	# Examined	Mercury (ppm)			
			Max	Min	Avg	Median
Station F3	Goldfish	1	.01	.01	.01	.01
	G. Shad	3	.04	.02	.03	.03
	Sunfish	1	.04	.04	.04	.04
	Brown Bullhead	4	.12	.02	.05	.035
	White Bass	8 sets (2 fish/set)	.33	.02	.07	.04
	Shad	18	.08	.02	.04	.04
Station F2	B. Bullhead	1	.31	.31	.31	.31
	Alewife	1	.09	.09	.09	.09
	W. Bass	2	.51	.09	.30	.30
	G. Shad	3	.05	.02	.03	.03

TABLE 4

RESIDUE ANALYSIS REPORT - AUGUST 14, 15, 16, 1972
Provincial Pesticide Residue Testing Laboratory

Content in tissues puree (ppm)

	Lab #	Species	Extractible Fat	DDE	DDD	DDT	TOTAL DDT	γ CHLORDANE	α CHLORDANE	HCB	PCB	DIELDRIN
Station F2	73-0453	B. Bullhead	2.92	0.65	0.18	0.03	0.86	Tr	0.02	0.02	7.3	0.01
	-0454	Alewife	8.43	0.47	0.14	0.07	0.68	0.03	0.04	0.06	3.5	0.02
	-0455	W. Bass	8.27	0.55	0.37	ND	0.92	0.05	0.08	0.06	1.5	0.02
	-0456	W. Bass	5.59	1.27	0.42	0.24	1.93	0.06	0.18	0.08	1.6	0.05
	-0457	Gizzard Shad	17.4	0.40	0.23	ND	0.63	Tr	0.04	0.01	1.4	0.01
	-0458	Gizzard Shad	18.8	0.45	0.32	Tr	0.77	0.02	0.04	0.08	3.0	0.03
	-0459	Gizzard Shad	18.1	0.42	0.40	ND	0.82	0.09	0.15	0.03	1.1	0.01
Station F3	-0460	Goldfish	23.4	1.26	1.02	0.04	2.32	0.47	0.61	0.07	11.7	0.09
	-0461	Gizzard Shad	19.9	0.67	0.62	0.05	1.34	0.05	0.09	0.14	4.0	Tr
	-0462	Gizzard Shad	17.6	0.54	0.60	0.10	1.24	0.05	0.15	0.06	3.2	0.05
	-0463	Gizzard Shad	11.0	0.24	0.24	Tr	0.48	0.05	0.14	0.02	1.7	0.01
	-0464	Sunfish	4.55	0.13	0.09	0.01	0.23	0.02	0.09	0.01	2.5	Tr
	-0465	B. Bullhead	4.18	0.47	0.18	ND	0.60	0.06	0.31	0.02	3.3	0.01
	-0466	B. Bullhead	5.83	0.21	0.11	ND	0.32	0.04	0.15	0.02	2.5	ND
	-0467	B. Bullhead	8.36	0.33	0.10	ND	0.43	0.08	0.30	0.04	3.3	0.01
	-0468	B. Bullhead	9.10	0.34	0.18	ND	0.52	0.05	0.14	0.04	3.4	0.01
		Average	6.87	0.34	0.13	ND	0.47	0.06	0.23	0.03	3.1	0.0075
		Median	7.1	0.34	0.12	ND	0.47	0.06	0.23	0.03	3.3	0.01
	-0469	(2 Fish) W. Bass	9.19	1.17	0.33	ND	1.50	0.03	0.14	0.23	11.8	0.04
	-0470	W. Bass	12.1	0.63	0.36	ND	0.99	0.06	0.39	0.13	6.2	0.03
	-0471	W. Bass	8.57	0.32	0.21	ND	0.53	0.04	0.13	0.05	4.8	0.01
	-0472	W. Bass	8.19	0.31	0.29	ND	0.60	0.03	0.22	0.04	5.0	0.02
	-0473	W. Bass	10.1	0.37	0.30	ND	0.67	0.04	0.39	0.06	5.8	0.01
	-0474	W. Bass	11.1	0.42	0.28	Tr	0.70	0.01	0.28	0.08	5.2	0.01
	-0475	W. Bass	9.64	0.53	0.44	ND	0.97	0.05	0.22	0.05	4.8	0.02
	-0476	W. Bass	9.51	0.54	0.48	ND	1.02	0.07	0.44	0.04	5.0	0.03
		Average	9.77	0.54	0.36	ND	0.87	0.04	0.28	0.09	6.1	0.02
		Median	9.57	0.47	0.32	ND	0.84	0.05	0.31	0.07	5.1	0.02

Station F3
(continued)

Lab #	Species	Extractible Fat	DDE	DDD	DDT	TOTAL DDT	γ CHLORDANE	α CHLORDANE	HCB	PCB	DIELDRIN
73-0477	Shad	10.1	0.54	0.46	ND	1.00	0.08	0.33	0.02	2.8	0.02
-0478	Shad	20.6	0.86	0.93	ND	1.79	0.04	0.14	0.05	6.8	0.04
-0479	Shad	18.4	0.48	0.46	ND	0.94	0.16	0.31	0.05	3.5	0.03
-0480	Shad	15.9	0.60	0.44	ND	1.04	0.02	0.10	0.08	3.2	0.02
-0481	Shad	18.9	0.41	0.51	ND	0.92	0.03	0.14	0.06	4.7	0.02
-0482	Shad	18.5	0.72	0.46	ND	1.18	0.03	0.30	0.04	4.1	0.02
-0483	Shad	16.1	0.46	0.28	ND	0.74	0.02	0.12	0.07	3.5	0.01
-0484	Shad	15.9	0.52	0.51	ND	1.03	0.03	0.14	0.04	6.2	0.02
-0485	Shad	16.6	0.42	0.33	ND	0.75	0.09	0.20	0.06	3.7	0.03
-0486	Shad	17.3	0.33	0.43	ND	0.76	0.01	0.09	0.04	3.5	0.01
-0487	Shad	17.6	0.51	0.56	ND	1.07	0.03	0.07	0.03	7.0	0.02
-0488	Shad	20.5	0.37	0.21	ND	0.58	0.04	0.15	0.03	5.1	0.02
-0489	Shad	17.9	0.51	0.22	ND	0.73	0.02	0.22	0.07	5.0	0.02
-0490	Shad	17.1	0.47	0.31	ND	0.78	0.03	0.09	0.05	3.4	0.02
-0491	Shad	24.7	0.38	0.19	ND	0.57	0.03	0.09	0.13	4.0	0.01
-0492	Shad	16.2	0.35	0.24	ND	0.59	0.09	0.17	0.03	6.0	0.05
-0493	Shad	17.4	0.25	0.17	ND	0.42	0.02	0.07	0.03	2.1	0.01
-0494	Shad	21.5	0.43	0.39	ND	0.82	0.08	0.16	0.03	5.2	0.03
	Average	18.0	0.48	0.39	ND	0.87	0.05	0.16	0.05	4.4	0.02
	Median	17.5	0.47	0.41	ND	0.87	0.03	0.15	0.05	4.1	0.02

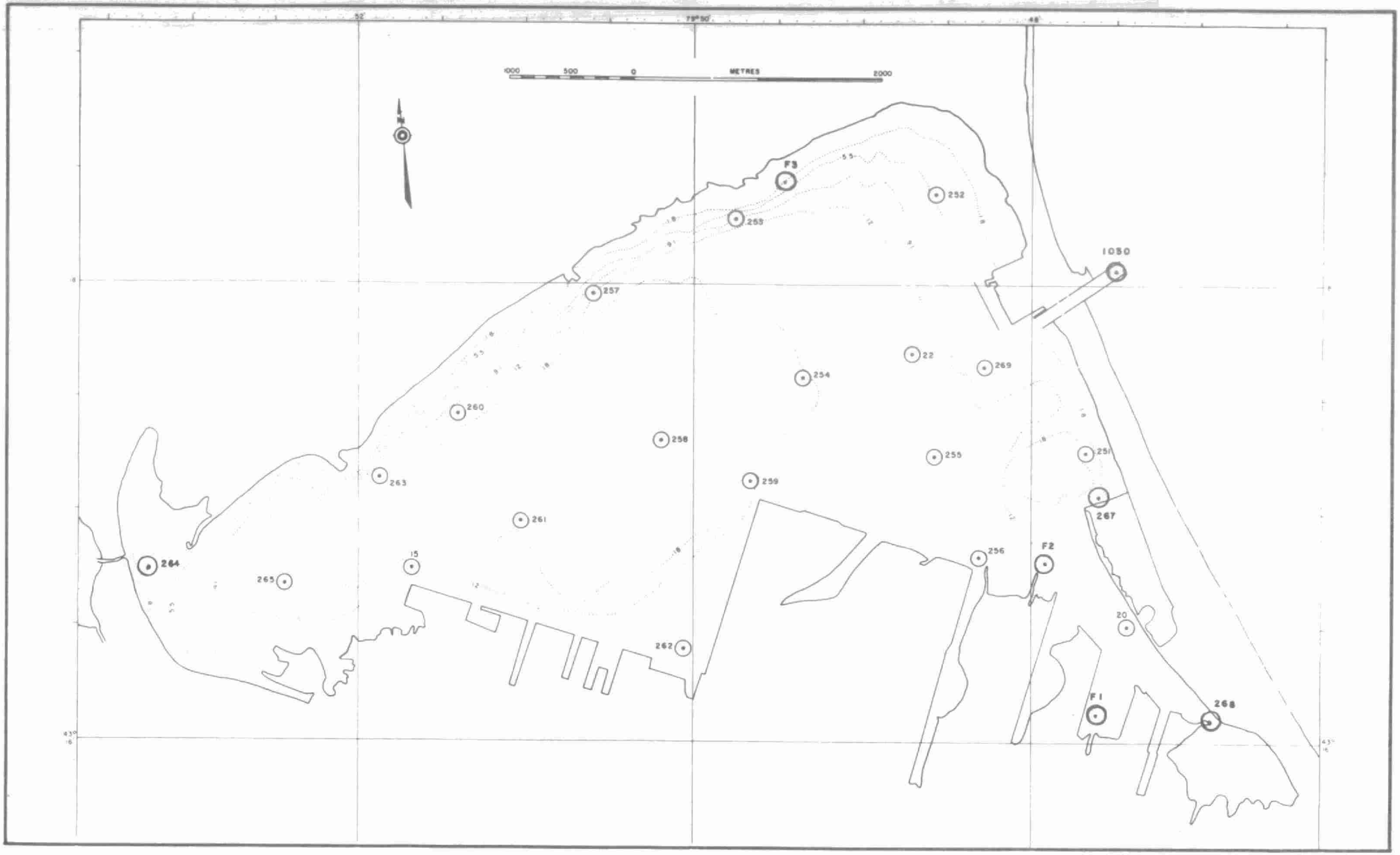


FIGURE 1 : HAMILTON HARBOUR

HAMILTON HARBOUR STUDY

section H

survey data

HAMILTON HARBOUR STUDY

Survey Data

The following chemical and physical parameters were measured and are presented as a summary in this section.

For each of these parameters there are 10 individual tables present in this section. First three tables are surveys for all measurements by stations, depths, and dates, respectively. The heading of each table contains all the important information - parameter, station numbers which were sampled, depths at which the individual samples were taken and the number of days on which the samples were collected. This is followed with the arithmetic mean, standard deviation, and the total number of data points for the given parameter and by a statement on how the data are listed, e.g. by stations, by depths or by dates. The columns in order are station identification (or depth or date), the arithmetic mean, standard deviation and $F=s_1^2/s_2^2$ where s_1^2 and s_2^2 are the variance of the total in the set and the variance at the individual stations (depth, date). Their values are arranged to fulfill the definition condition that F is greater than 1. The number of measurements used for the calculation of standard deviation in the numerator (NNU) and denominator (NDE) are given. By using the standard F-test tables it can be determined if the measurements at the individual station (or depth, or date) are significantly different from the set of all measurements; the degrees of freedom for the test are NNU-1 and NDE-1.

The data were also partitioned into epilimnetic and hypolimnetic data sets and presented in a similar manner. The type of data set is clearly identified by a statement on each page of printout.

Data were classified as epilimnetic or hypolimnetic using temperature - depth data collected concurrently. The location of the thermocline was established from the second derivatives of the temperature - depth profiles. Cases on non-stratification or insufficient temperature profile data were omitted from the stratified sub-sets.

The last table for a given parameter gives a summary of the sets. It includes the total number of measurements along with the number of measurements in the epilimnion and hypolimnion sets. Data omitted from the stratified sub-sets are listed as unclassified

The data are available on request from the Librarian, Ontario Ministry of the Environment, 135 St. Clair Avenue West, Toronto, Ontario, (416) 965-7978.